

# Review of numerical studies on thermal treatment of municipal solid waste in packed bed combustion

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## ABSTRACT

Municipal solid waste (MSW) is increasingly considered a source of energy and materials rather than an environmental and socioeconomic problem. Incineration using the grate-firing technique is one of the best available technologies for thermal treatment of non-recyclable MSW with energy recovery. The transition to a circular economy brings a new challenge to the Waste to Energy (WtE) industry. Due to advanced waste management schemes, the calorific value of the input waste is likely to decrease. Nevertheless, WtE plant designers and operators have aimed to increase the energy and material recovery efficiency of their installations, while maintaining or even decreasing operation and maintenance costs. For these reasons, there is a need for better understanding of the chemical and physical phenomena involved in the MSW incineration process. Accurate numerical modelling of MSW packed bed combustion can substantially contribute to this objective.

The literature on similar fields such as coal and biomass combustion has delineated many crucial aspects of modelling solid fuel combustion in grate-firing applications. However, the know-how obtained in these fields cannot be one on one transferred to MSW incineration because MSW is much more inhomogeneous in composition and thermophysical properties. This paper first presents an overview of MSW's chemical and thermophysical properties. Then, the heterogeneous nature of MSW and its complex thermal degradation behaviour are used as a basis to discuss the suitability of the available numerical methodologies. Finally, current challenges in the modelling of waste beds are identified, with relevance to improving the performance of industrial WtE plants.

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## 1. Introduction

### 1.1. Municipal solid waste

The World Bank has estimated that 210 million tonnes of municipal solid waste (MSW) were generated worldwide in 2016, and this amount is expected to increase 1.7 times by 2050 [1]. In Europe, the total MSW generated by EU-28 countries amounted to 167.10 million tonnes in 2016 and has been stable since 2012 [2]. These data show the need for more sustainable MSW management and treatment. In countries that have a long history of waste pol-

icy and management, waste is no longer considered a burden, but rather a source of energy and materials.

In 2015, the European Commission proposed the existing EU waste hierarchy within a new "Circular Economy" concept [3]. In order of priority, waste has to be treated by "preparing for reuse", "recycling", "recovery", and "disposal". Even though recycling is ranked higher in the hierarchy than recovery, it has economic and technical limitations. From this perspective, Van Caneghem et al. [4] defended that waste recovery (in particular, conventional Waste to Energy – WtE) is complimentary and compatible with recycling because of two reasons. Firstly, WtE can destroy and eliminate toxic substances in waste. If products containing these substances are recycled, processing costs will increase, and the quality of the recycled materials might deteriorate. Secondly, WtE not only

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**Nomenclature**

$A$	Momentum exchange due to particle random movement ( $\text{N/m}^3$ )
$A$	Pre-exponential factor
$A$	Surface area ( $\text{m}^2$ )
$A_C$	Char surface area ( $\text{m}^2$ )
$A_f$	Bed surface area ( $\text{m}^2$ )
$Bi$	Biot number (-)
$C$	Gas concentration ( $\text{kmol/m}^3$ )
$C_s$	Solid concentration ( $\text{kg/m}^3$ )
$C_{pg}$	Specific heat capacity of the gas phase ( $\text{J/kgK}$ )
$C_{ps}$	Specific heat capacity of the solid phase ( $\text{J/kgK}$ )
$d_p$	Particle diameter (m)
$d_{p\_small}$	The smaller diameter of two contacting particles (m)
$D$	Molecular diffusion coefficient ( $\text{m}^2/\text{s}$ )
$D_e$	Effective diffusivity of the ash layer ( $\text{m}^2/\text{s}$ )
$D_{ig}$	Dispersion coefficient of the gas species $i$ ( $\text{m}^2/\text{s}$ )
$D_s$	Particle mixing coefficient due to random movements of particles in the bed ( $\text{m}^2/\text{s}$ )
$e$	Coefficient of restitution of particle collisions
$E$	Activation energy ( $\text{J/mol}$ )
$f_{ash}$	Mass fraction of ash in the solid bed (-)
$f_e$	Empirical correction factor accounting for the bed packing (-)
$F$	Weight factor (-)
$F_{ij}$	View factor
$g$	Acceleration of gravity ( $9.81 \text{ m/s}^2$ )
$g_0$	Radial distribution function of the solid phase
$G$	Incident radiation ( $\text{W/m}^2$ )
$h_{pn}$	Heat transfer coefficient between particles ( $\text{W/m}^2\text{K}$ )
$h_c$	Convective heat transfer coefficient ( $\text{W/m}^2\text{K}$ )
$h_{pn}$	Heat transfer coefficient between particles
$H_s$	Solid enthalpy ( $\text{J/kg}$ )
$k_g$	Gas thermal conductivity ( $\text{W/mK}$ )
$k_s$	Thermal conductivity of the solid phase ( $\text{W/mK}$ )
$k_{eff}$	Effective thermal conductivity ( $\text{W/mK}$ )
$k$	General rate constant
$k_r$	Kinetic rate constant of char burning
$k_d$	Diffusion rate constant of char burning
$k_{global}$	Effective rate constant of char burning
$m$	Solid mass (kg)
$M_C$	Molecular weight of char ( $\text{kg/kmol}$ )
$m, n$	Reaction order (-)
$n_p$	Number of particles (-)
$Nu$	Nusselt number (-)
$NP_a$	Number of contacting particles in the same waste lump (representative particle model)
$NP_b$	Number of contacting particles in a different waste lump (representative particle model)
$P$	Pressure (Pa)
$P_i$	Partial pressure of the gas species $i$
$Pr$	Prandtl number (-)
$Py$	Pyrolysis number, relating to the internal heat transfer (-)
$Py'$	Pyrolysis number, relating to the external heat transfer (-)
$q_r$	Radiative heat flux ( $\text{W/m}^2$ )
$Q_{sh}$	Thermal source term for solid phase ( $\text{W/m}^3$ )
$r$	Radius (m)
$r_p$	External radius of straw (m)
$r_{p,in}$	Internal radius of straw (m)
$R$	Universal gas constant ( $8.314 \text{ J/molK}$ )

$R$	Rate expression
$R_c$	Thermal resistance ( $\text{W/K}$ )
$Re$	Reynolds number (-)
$S$	General source term
$S_a$	Active surface of char
$S_V$	Internal volumetric surface area ( $\text{m}^2/\text{m}^3$ )
$Sh$	Sherwood number (-)
$t$	Time instant (s)
$T_g$	Gas temperature (K)
$T_p$	Particle temperature (K)
$T_{pn}$	Temperature of $n^{\text{th}}$ particle (representative particle model)
$T_s$	Solid temperature (K)
$T_{wall}$	Furnace wall temperature (K)
$T_\infty$	Freeboard temperature (K)
$u_B$	Horizontal velocity of the moving bed (m/s)
$u_g$	Gas velocity (m/s)
$u_s$	Average velocity of solid particles (m/s)
$V$	Bed volume ( $\text{m}^3$ )
$X$	Conversion degree (-)
$X_C$	Conversion rate of char
$Y$	Mass fraction (-)
$Y_{is}$	Mass fractions of solid compositions (moisture, volatile, fixed carbon, and ash)
$W$	Total mass (kg)
$Z$	The distance in the direction of dispersion (m)
$\vec{F}$	Forces that apply on the particle (drag force, gravitational force and other forces) ( $\text{kgm/s}^2$ )
$\vec{u}_p$	Particle velocity vector
$\dot{Q}_i$	Radiation energy leaving the surface $i$ (W)
$\dot{Q}_{ij}$	Radiation heat from particle $i$ to particle $j$ (W)
$\dot{Q}_{pp}$	Direct contact heat transfer between particles (W)
$\dot{Q}_{rad}$	Radiation heat transfer (W)
$\dot{Q}_{surface}$	Supply heat from the freeboard to the bed surface (W)

**Greek letters**

$\alpha_j$	Absorption coefficient of the particle $j$
$\alpha$	Empirical shrinking coefficients (-)
$\alpha$	Conversion degree (-)
$f(\alpha)$	Reaction model function
$\beta$	Gas-solid interphase drag ( $\text{kg/m}^3\text{s}$ )
$\delta_{ash}$	Ash layer thickness (m)
$\varepsilon$	Emissivity (-)
$\Theta_s$	Granular pseudo-temperature ( $\text{m}^2/\text{s}^2$ )
$\rho$	Density ( $\text{kg/m}^3$ )
$\rho_s$	Intrinsic solid density ( $\text{kg/m}^3$ )
$\rho_{sb}$	Bulk density of the bed ( $\text{kg/m}^3$ )
$\sigma$	Normal stress tensors (Pa)
$\sigma$	Stefan-Boltzmann constant ( $5.67\text{E-}8 \text{ W/m}^2\text{K}^4$ )
$\sigma$	Standard deviation
$\tau$	Shear stress tensors (Pa)
$\tau_s$	Solid stress (Pa)
$\nu$	Stoichiometric ratio (-)
$\phi$	Bed porosity (-)
$\varphi$	Empirical factor (-)
$\psi$	Pore structure parameter (the RPM model)

**Subscripts**

$a, b, x, y$	Empirical constants
$b$	Bed
$C$	Char
$C$	Cardboard
$C$	Cellulose

<i>f</i>	Final value
<i>g</i>	Gas phase
<i>M</i>	Moisture
<i>NC</i>	Non-cellulose
<i>I</i>	Intermediate solid species
<i>p</i>	Particle
<i>PE</i>	Polyethylene
<i>s</i>	Solid phase
<i>sb</i>	Solid bed
<i>vol</i>	Volatiles
<i>VM</i>	Volatile matter
<i>0</i>	Initial value
$\infty$	End value

recovers energy from waste which is non-recyclable for economic or technical reasons but also allows recovery of some materials such as metals and minerals. As a consequence, WtE will probably never be phased out completely; yet there is still potential for improving energy and material recovery. Because of this, scientific research on WtE remains imperative.

Thermal treatment is a conventional way to recover energy and materials from waste. Table 1 summarises the commonly-known thermal WtE techniques:

*Torrefaction* is a pre-treatment technology in which solid fuels are heated at relatively low temperature in the absence of oxygen to remove moisture and part of the volatiles [5]. The treated material has a higher heating value and is less heterogeneous in composition. Thus, it becomes more suitable as an energy source in thermal conversion processes. The application of torrefaction has been extensively investigated for biomass, but studies on waste are still very limited [6,7].

*Pyrolysis* is growing as an alternative application for MSW in which waste is treated in the absence of oxygen to produce syngas or liquid products. Pyrolysis of MSW does not generate but consumes energy to convert the waste into gaseous and liquid flows, which are rather used as raw materials than as fuel [5,8–10].

*Gasification* is also a destructive process that converts waste to syngas in a sub-stoichiometric oxygen environment. This technique requires pre-treatment of MSW since it is sensitive to changes in waste composition [5,10,11].

*Incineration* is a technique in which super-stoichiometric amounts of oxygen are applied to combust the organic part

of the solid waste completely [10]. The released heat of combustion is used for steam generation, which can then be applied directly as a heat source or can be sent to a turbine for electricity production. The overall gross energy efficiency of MSW incineration varies from 30% if all steam is used for electricity production up to 80% if all steam is applied as a heat source. One advantage of waste incineration is that it typically reduces the waste mass by 70% and the volume by 90% [8,9]. In addition, incineration is a simple, proven technique that offers great flexibility in treating solid fuels with a wide variation in composition, size and properties [12]. Furthermore, it is suitable to treat waste containing toxic substances, thanks to the high operating temperatures and the mature development of the flue gas cleaning system.

Lombardi et al. [9] conducted an extensive study about the differences between incineration, gasification and pyrolysis from published data on plants across Europe, the USA and some other countries. Scientific studies show that incineration and gasification plants have comparable energy recovery potentials. However, the overall energy efficiency of gasification plants might be lower if the energy loss during the necessary pretreatment processes is included. Additionally, because gasification plants are complex, their investment and operational costs might be higher than those of conventional WtE plants [4]. Regarding pyrolysis, although research has shown its potential, there are only a few documented in industrial applications, which are restricted to pure and homogeneous waste streams [9].

Nevertheless, the fundamental chemical and physical phenomena behind all four techniques are quite similar as the solid waste, being exposed to high temperatures, undergoes similar consecutive sub-processes, i.e., heating-up, drying, devolatilisation (i.e., pyrolysis), and combustion (if oxygen is present). Because of this, a study of, e.g., pyrolysis of solid waste is also relevant for incineration. In this paper, we focus mainly on incineration as it is still the most widely-used technique for thermal treatment of MSW in practice (e.g., around 27% of MSW produced in EU-28 was treated by incineration in 2015 [13]).

## 1.2. Design and optimisation of waste incineration plants

About 90% of the MSW incinerators in Europe use grates because they are reliable, have a high capacity and adaptability to waste, and are convenient to operate and maintain [13]. A grate incinerator basically consists of five parts: the waste feeder, the

**Table 1**  
Comparison of different thermal waste treatment techniques.

	Torrefaction	Pyrolysis	Gasification	Combustion (i.e., Incineration)	Ref.(s)
Atmosphere	Inert atmosphere	Oxygen-deficient	Limited oxygen	Excess oxygen	[5,8,10]
Temperature	200–350 °C	300–1300 °C	800–1200 °C	750–1100 °C	[5,8]
Pressure	–	1 bar	1 – 45 bars	1 bar	[13]
Key products	Char	Char + liquid fuel (tar) + syngas	Syngas (CO, H <sub>2</sub> , CO <sub>2</sub> , CH <sub>4</sub> , light HCs)	CO <sub>2</sub> , H <sub>2</sub> O + heat	[5]
Thermochemistry	Endothermic	Endothermic	Exothermic	Exothermic	[5]
Heating rate	–	Slow (10 °C/min); Fast (up to 600 °C/sec)	–	Intermediate	[5,14]
Type of waste	Food waste, PVC plastic, discarded tyres, and wood residues	Treated MSW (removal of glass, metal, inert, contaminants)	Treated MSW (removal of glass, metal, inert, contaminants)	Mixed MSW	[5,15]
Technology	Rotating drum, screw-type reactors, multiple hearth furnace, torbed reactor, moving compact bed, belt dryer, microwave reactor	Rotary kiln / tubular reactor (up-scaled facilities) Fixed-bed and fluidised bed reactors (lab-scale studies)	Entrained flow gasifier, fluidised bed gasifiers, cyclone gasifiers, packed-bed gasifiers	Fluidised bed, spouted bed, fixed bed (rotary kiln, grate-firing)	[5,6,14]

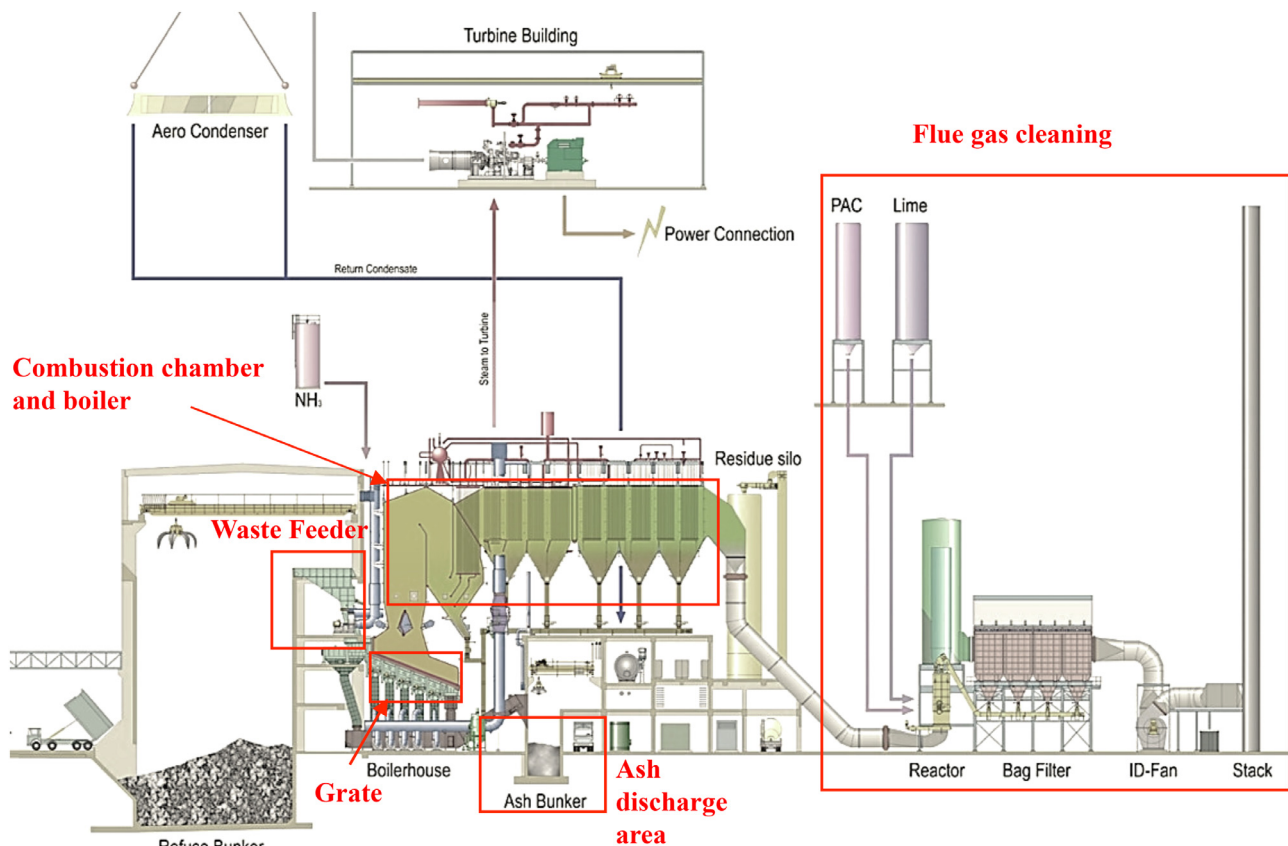


Fig. 1. Example of a WtE plant with a moving grate [16].

grate, the combustion chamber and boiler, the ash discharge area and the flue-gas cleaning zone (See Fig. 1). The waste is unloaded from trucks to the storage bunker and from there fed into the waste feeder by a grabbing crane. At the bottom of the waste feeder, the waste is pushed on the moving grate, where it is exposed to radiation heat from the chamber above and to primary air fed from the bottom. Along the grate, the solid waste is heated up, undergoing moisture evaporation and devolatilisation. In a latter step, the waste is pyrolysed, after which the remaining char is gasified and oxidised. At the end of the grate, the remaining ash is collected at the discharge area. The volatiles released from the waste react with the secondary air that is injected in the combustion chamber. The generated hot flue gas flows through the boiler where it transfers heat to water in steel tubes to produce steam. The produced steam can generate electricity in a turbine or can be applied as a heat source. The cooled down raw combustion gases, containing a high amount of pollutants, are thoroughly cleaned before they are released through the stack.

A WtE plant has to be designed and operated so that it offers high flexibility in terms of waste composition and capacity. Indeed, MSW can be very heterogeneous in composition and properties, and the produced mass can fluctuate considerably over time [14]. Historically, the development of WtE plants has been guided by the variable composition of MSW and strict regulations for emissions and residue disposal [17,18]. In comparison with conventional power plants combusting coal and other solid fuels, modern WtE plants have more stringent emission limit values (ELVs) for total dust, SO<sub>2</sub>, NO<sub>x</sub>, CO, TOC, HCl, HF and heavy metals [18]. Hence, the environmental impact of modern WtE plants is low [18,19].

Although the process and environmental control of WtE plants has been significantly improved over the last decades, some aspects could still be further developed in the current societal and

legislative context. According to De Greef et al. [17], the main opportunities for improvement are: 1) Further enhancing the operational stability of waste combustion, 2) Improving the efficiency of the Selective Non-Catalytic Reduction (SNCR) system to minimise NO<sub>x</sub> emissions and 3) Developing a cost-effective solution for deposit formation and high-temperature corrosion. A thorough understanding of combustion processes, by means of numerical and experimental studies on different process levels, taking into account the complexity and forecasted compositional changes of MSW, is imperative to tackle these challenges.

### 1.3. Numerical studies on waste incineration

Design, optimisation and control of WtE processes require knowledge at multiple levels. An experimental approach can offer verifiable observations and analysis but requires expensive setups. Furthermore, in some parts of waste incinerators, measurement of process variables is difficult and safety is a concern. In this regard, a numerical approach is a promising complementary tool. Fig. 2 illustrates the different levels of numerical studies for WtE design and optimisation.

In WtE plant operation, there is always a trade-off between economic, environmental, and operational aspects. A study concerning all three aspects is called a *multi-objective optimisation study*, which provides a decision support tool for operators when trade-offs in plant performance objectives are expected [20–22]. This kind of study requires an in-depth knowledge of the whole plant operation, which can only be obtained by conducting process simulations (i.e., system-based simulations) or studying individual processes (e.g., the grate furnace simulations).

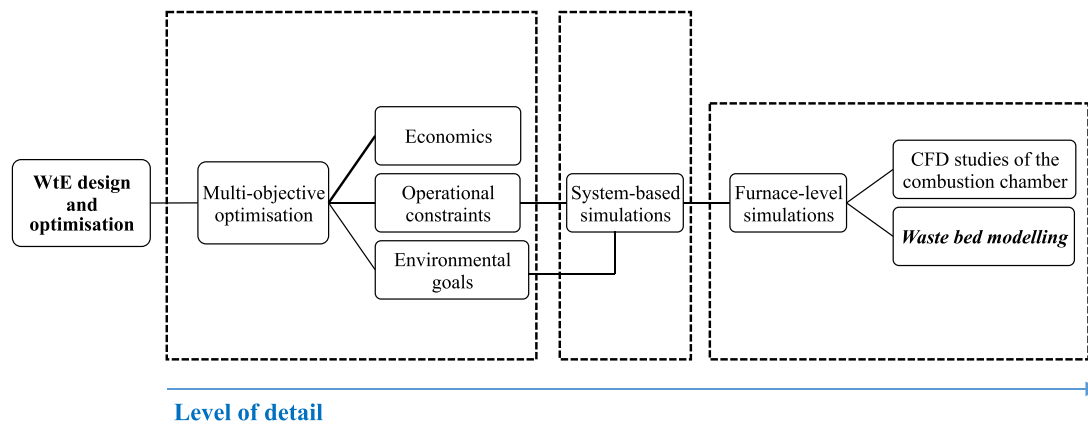


Fig. 2. Numerical studies for WtE design and optimisation.

A *system-based simulation* incorporates the grate furnace with utilities such as the heat exchangers, pumps, condensers, and turbines, all of which are considered as components of a global thermodynamic system. A study conducted at the static equilibrium, based on thermodynamics and chemical laws [21], is usually needed to design such a system. For more advanced information regarding the transient operation, a more complex model called dynamic simulation is required. Both types of simulations can be carried out using software such as ASPEN Plus Dynamics, Dymola, Matlab/Simulink or APROS [23]. An advanced system-based simulation for a WtE plant has recently been developed by Alobaid et al. [24]. This model simulates the real-life behaviour of an MSW incinerator throughout the entire operational range. It is a time-dependant simulation in which non-linear, transient, one-dimensional partial differential equations, together with correlations of friction loss and heat transfer, are solved. Nevertheless, dynamic system-based simulations rely on the characterisation of the dynamic behaviour of all system components, which can be difficult to model and validate against field data.

A more detailed level of simulation is the *furnace-level simulation*. This type of study takes into account not only mass and energy conservation but also transport phenomena. A furnace consists of two parts: the solid bed (i.e., the grate) and the freeboard (i.e., the combustion chamber). The modelling strategy for a furnace is principally the same for all grate types (e.g., stationary sloping grates, moving grates, vibrating grates, and reciprocating grates) [25], involving three types of mathematical models: computational fluid dynamics (CFD), fuel bed and stochastic models [26]. Over the last decades, CFD has provided a versatile means to simulate the reacting dilute two-phase flow in the freeboard, but a comprehensive model for the bed region has not yet been developed. This paper gives an overview of the state-of-the-art of waste bed modelling and provides some extra information on stochastic models since they allow to include grate mixing and waste heterogeneity.

#### 1.4. Paper structure

The primary aim of this paper is to assess the applicability of existing fuel bed modelling techniques to MSW. To this end, it is vital to understand the heterogeneous compositions and properties of MSW as they are key parameters for the correct choice of model settings.

The main part of the paper discusses the current state-of-the-art of modelling MSW combustion in packed beds, without being

redundant with previous work on the modelling of thermal conversion of coal and biomass. For the latter, readers are referred to the work of Di Blasi [27] and Haberle et al. [28], which provides background on chemical and physical processes in thermal degradation of lignocellulosic biomass with a focus on the particle level. Additionally, Dernbecher et al. [29], Rahdar et al. [30], and Khodaei et al. [31] did excellent reviews on specific modelling approaches for biomass combustion systems, including sub-models for NO<sub>x</sub> formation, particulate emissions and the decomposition of pollutants (dioxin, furan, chlorobenzene, chloroform etc.). Focusing more on operational aspects, Yin et al. [32] discussed several key issues in biomass grate-firing systems and made suggestions for future research and development.

This paper is structured as follows:

- 1) [Section 2](#) reviews the heterogeneity of MSW, covering a wide range of MSW compositions, and properties.
- 2) [Section 3](#) briefly reviews the modelling approaches of packed beds with a focus on MSW applications.
- 3) [Section 4](#) is devoted to sub-models for the thermal conversion of the complex multi-component MSW, focusing on kinetic studies of MSW pyrolysis.
- 4) [Section 5](#) gives an overview of some specific processes and considerations in the modelling of MSW grates and briefly discusses the relevant stochastic models.
- 5) [Section 6](#) states the current understandings of MSW fuel beds which are derived from existing parametric studies using the numerical approach.
- 6) [Section 7](#) discusses the challenges in MSW bed modelling and outlines possible future research in the field that support solutions for the current issues in modern WtE plants.

## 2. Heterogeneity of MSW

MSW, by definition, is garbage consisting of everyday items that are discarded by the public. Basically, MSW contains food waste, paper and cardboard, garden waste, wood, plastics, rubber and leather, textile, metals, glass, and other non-combustible wastes [14,33]. MSW compositions and properties vary hugely, but in most cases, the largest fraction is food waste, followed by non-combustibles, paper and cardboard, and plastics [1,15,34–40]. More specifically, the variability of MSW is a consequence of many factors, such as economic status, cultural preference, climate and local waste management policies [34,37]. As the income level of the population rises, the fraction of plastic and paper in consumed goods and eventually in the produced waste typically increases [1]. High-income countries tend to impose stricter waste collection and sorting strategies which significantly influence the MSW compo-



sition [1,35]. Seasonal changes, the occurrence of holiday periods, weekends and special events also have a direct impact on MSW composition [17].

The variability in MSW composition is a huge challenge not only for the design and operation of industrial plants but also in research. In industry, the composition of MSW is typically obtained via a standard waste audit [1], which is impossible to conduct on a regular basis for the MSW entering commercial incinerators. In research, a comprehensive set of data on physical and chemical characteristics of different waste fractions and their share in the MSW mix is missing. This lack impedes scientists to fully progress in acquiring a broader insight into MSW thermal degradation processes.

The following sections discuss the chemical composition and thermophysical properties of MSW which are relevant for numerical studies. The chemical composition data were taken from published studies on MSW collected in different cities/regions in the world [15,34–43]. They are listed in Table 1 – Supplementary Material Section.

## 2.1. Chemical composition of MSW

Based on the thermal degradation characteristics of the individual waste components, MSW can be divided into five fractions: food waste, lignocellulosic materials, plastics, other combustibles and incombustible materials [44].

MSW contains a high amount of *food waste*, varying from 15 wt.% [41] to more than 50 wt.% [34,36,39]. Food waste comprises mainly moisture, lignocellulosic materials (e.g., in vegetables and fruit peels), protein (e.g., in meat) and starch (e.g., in banana, rice, and bread). The thermal degradation characteristics of lignocellulosic materials and proteins are quite similar, whereas starch decomposes at relatively lower temperatures and can thus be considered as a low stability organic component [44].

Paper and cardboard, wood, garden waste (i.e., yard waste or green waste) and textile (mainly cotton) can be classified as the *biomass fraction of MSW*<sup>1</sup> as they are primarily composed of hemicellulose, cellulose and lignin. These components have a pyrolysis behaviour similar to that of woody biomass and can be regarded as “lignocellulosic materials” [44].

Approximately 90% of the *plastics* in MSW consist of polyethylene (PE), polypropylene (PP), polyvinyl chloride (PVC) or polystyrene (PS) [20,34]. Except for PVC, plastics (called chlorine-free plastics) have a similar thermal degradation behaviour and are therefore often grouped into one pseudo-component [44]. PVC decomposes in two steps, i.e., dehydrochlorination and degradation of the remaining hydrocarbon residual [44].

MSW contains a significant amount of *other combustibles* such as tyres (or rubber), leather, textiles, tetrabricks or diapers [15,35,37,38,40–42]. Textiles, containing natural or synthetic fibres, can be added to the biomass and plastic fractions. Tyres are highly complex materials as they contain more than 100 different substances such as rubber polymers (50 wt.%), carbon black, silica, steel, sulphur and metal oxides (e.g., zinc oxides) [45,46]. The rubber polymers are predominantly composed of natural rubber (NR), styrene-butadiene rubber (SBR) and butadiene rubber (BR) [47]. Leather is a product processed from animal skin which contains mainly protein [48].

The *incombustible fraction* of MSW consists of inert material such as glass, ceramics, sand, metals and other minerals [15,34–43].

Of all MSW fractions, the moisture content in food waste is the highest, i.e., more than 50 wt.% and usually around 70 wt.% [34]. Garden waste can have a moisture content as high as food waste [49], while the average moisture content of other biomass components is rather moderate, ranging from 5 wt.% to 30 wt.% [34]. Leather has a relatively low moisture content (12 wt.%) [50], followed by other MSW fractions.

On a dry basis, the volatile matter (VM) content of the biomass fraction of MSW is 70 to 90 wt.% [51], followed by food waste with a VM content of 70 wt.% [34]. Except for PVC, plastics have a very high VM content (practically 100 wt.%) [44]. The VM content of leather is comparable with that of tyres and PVC and is well over 50 wt.% [48].

Amongst all combustible components, rubber has the highest ash and fixed carbon content [52]. On a dry basis, the biomass and food fractions of MSW have relatively 5 to 10 wt.% of fixed carbon and up to 20% of ash content [34,51]. Unlike other plastics, PVC has a high amount of fixed carbon (5 wt.%) [51,52].

Ultimate analysis on a dry ash-free basis (daf.) shows that chlorine-free plastics consist mainly of C and H [44], unlike PVC that contains up to 50 wt.% of Cl [51,52]. The main fractions of MSW, i.e., food waste and biomass, contain 50 wt.% of C, followed by O (40 wt.%), H (7 wt.%) and N (2–4 wt.%) [34]. Rubber contains a high fraction of C (84 wt.%) and H (9 wt.%), and a small amount of O, N, S and Cl [34]. Leather contains mainly C (47 wt.%) and O (44 wt.%), and a detectable amount of H, S and N [48].

The calorific value (lower heating value, LHV) of MSW depends on its composition, which is reflected in the proximate and ultimate analysis. The higher the C and H content (daf.) in the MSW, the higher the LHV. Moisture and ash content, on the contrary, lower the LHV of MSW. Accordingly, a high fraction of food and garden waste induces a high moisture content and correspondingly a low calorific value. Non-combustibles are undesirable, not only because they play a significant role in the formation of pollutants and ash but also because they reduce the LHV. Plastics, except for PVC, usually secure a high energy recovery potential (e.g., LHV up to 43,910 kJ/kg for PP [52]) with low ash and moisture content. Also, rubber has a high LHV (29,410 kJ/kg), followed by lignocellulosic materials (e.g., 17,280 kJ/kg for poplar wood) [52].

The collected data (Table 1, Supplementary Material) highlight the inherent uncertainty on the MSW composition, which makes it challenging to simulate MSW combustion accurately. Overall, an analysis of MSW fractions suggests several major aspects that require attention when conducting numerical modelling of the thermal degradation of MSW. As stated above, MSW generally has a high moisture content due to the presence of food waste and a high ash content due to the presence of non-combustibles. Therefore, it is necessary to accurately model the moisture evaporation process and the ash-related phenomena. MSW also contains a considerable amount of lignocellulosic materials and plastics, which have a high VM content. Thus, when dealing with pyrolysis, a reasonably-accurate fuel bed model will need to include both biomass and plastic fractions. Depending on the specific MSW composition, the thermal degradation of low stability organic components, tyres and leather has also to be included in the bed model. For studies involving trace elements such as Cl and metallic elements, a specific focus has to be given to PVC and non-combustible fractions.

So far, most of the numerical models of thermal degradation of MSW in packed beds only consider the lignocellulosic fraction (e.g., woody biomass). In lab-scale studies [25,53–57], the simulated waste was prepared by mixing several lignocellulosic frac-

<sup>1</sup> According to the definition of biomass as biodegradable material of recently living organisms, food waste is also biomass and is counted as such when referring to the renewable fraction of MSW.

tions of MSW (e.g., wood, cardboard, paper, vegetable) with water and inert materials to obtain a higher moisture and ash content. Studies of pilot/full-scale waste incinerators used local MSW compositions [58–65]. Fuels similar to MSW, such as Solid Recovered Fuel (SRF) or Refused Derived Fuel (RDF) were also investigated [62,66]. As shown in Table 2, there is a great variety of MSW compositions considered in existing packed-bed models. For instance, the considered moisture content ranges from 8.8% to 49.2% [57] and the ash content ranges from 2.9% [55] to 36.4% [60]. The LHV of waste input varies from 4390 kJ/kg [57] to 22,741 kJ/kg [53]; particularly for real MSW, values between 6600 [65] and 10,670 kJ/kg [60] were reported.

## 2.2. Thermophysical properties of MSW

Modelling thermal degradation of MSW is known to be complicated because heat and mass transfer and conversion processes are inter-dependant. Studies on feedstock comparable to MSW, such as coal and biomass, have suggested that the thermophysical properties of the MSW are of utmost importance. MSW properties include density, permeability, thermal conductivity, specific heat capacity, size and shape of so-called particles [28]. In the literature, no solid set of empirical data on thermophysical properties exists, and there is also no consensus on model assumptions. This is already the case for coal and biomass [28] and becomes an even bigger challenge for MSW given the higher level of uncertainty on its composition and the irregular shape of the “particles” it contains.

Data on thermophysical properties reported in related studies, e.g., on the collection of MSW or on MSW landfills, offers some insights. The bulk density of MSW during different handling steps varies from 90 to 150 kg/m<sup>3</sup> for loose garbage, 180 kg/m<sup>3</sup> in waste bins, 350 to 420 kg/m<sup>3</sup> in collection trucks and 420 to 1000 kg/m<sup>3</sup> in landfills [67]. MSW stacked in a bed on the grate might have similar densities as MSW in a collection truck or in the fresh layer of a landfill. Numerical studies considered a bulk density of the waste bed between 111.5 and 360 kg/m<sup>3</sup> [25,53,54,56,57,62,68], which is somewhat lower than in collection trucks or landfills. With a material density of MSW of approximately 1650 kg/m<sup>3</sup> [69], the total porosity of the bed can vary from 0.4 to 0.95, which is a considerable range. However, the effective porosity (based on interconnected voids) is more relevant in packed layers of heterogeneous porous materials such as MSW. Unfortunately, to the authors' knowledge, the effective porosity of MSW beds on grates in WtE plants has not been investigated so far. Studies on waste bed modelling assumed effective porosities between 0.3 and 0.65 [25,54,56]. These values were used to estimate the permeability of packed beds based on Darcy's law [25]. Using this approach, the lowest gas permeability that can be estimated is 1.3E-7 m<sup>2</sup>, assuming a solid particle diameter as low as 12 mm [71]. Studies on hydrodynamic properties of MSW packed layers in landfills show much lower gas permeability values, i.e., 1E-16 to 1E-9 m<sup>2</sup> [69,70].

MSW particle size and shape must be known to make accurate assumptions related to the simulation of heat and mass transfer between the gas and solid phases. In practice, it is impossible to describe the size of irregularly-shaped MSW particles by single-valued functions. Instead, particle sizes should be expressed by a distribution curve, commonly between 2.54 to 254 mm [67]. However, in fuel bed modelling, the shape of MSW components is often oversimplified as spherical with uniformity in size (sizes from 12 to 270 mm [25,53,55,71]). Some efforts have been made to overcome this oversimplification. Matzing et al. [62], for instance, replaced the particle size by a plain specific surface in order to account for the arbitrary shape of MSW components. Furthermore, Yang et al. [72] and Wissing et al. [60] included a discrete distribution of particle sizes in their models.

**Table 2**  
Proximate and ultimate analysis of MSW with relevance for fuel bed modelling.

Ref. (s)	Feedstock	Proximate analysis (wt.%)				Ultimate analysis (wt.%)					
		Moisture	Volatiles	Fixed C	Ash	LHV (kJ/kg)	C	H	O	N	S
[53]	Wood + cardboard + paper + vegetable	48.5	41.48	7.07	2.95	22,741	NA	NA	NA	NA	NA
[54]	Pinewood + moisture + ash	25	NA	NA	10	10,041.6	48.20*	7.15*	44.65*	NA	NA
[55]	Wood + cardboard + paper + vegetable	48.5	41.53	7.07	2.9	6873	46.63*	5.77*	47.06*	0.27*	0.27*
[66]	MSW (75 wt.%) + RDF (25 wt.%)	29.0	55.5*	7.0*	37.5*	8300	32.4**	4.5**	40.7**	NA	NA
[58,59]	Local MSW	36.0	32.0	8.2	23.8	7655	50.2*	5.8*	42.3*	0.97*	0.63*
[56]	Cardboard + perishable materials + dry sand	26.5	38.25	4.55	30.7	6560	19.81	2.47	20.37	0.06	0.09
[57]	Vegetable + paper card + sand	8.8–49.2	39.5–86.67*	18.22–33.12*	4.29–7.09**	4390–9710	NA	NA	NA	NA	NA
[63]	Waste	12.10	64.55	17.86	5.49	NA	NA	NA	NA	NA	NA
[65]	Waste	10	66.2	16.6	7.2	6600	NA	NA	NA	NA	NA
[60]	MSW	23.67–29.59	36.02–44.49	3.95–8.83	21.4–36.36	8640–10,670	21.14–26.11	3.35–4.14	14.27–18.56	0.63–0.78	0.05–0.19
[61,62]	MSW	29.59	NA	NA	24.66	8640	23.47	3.36	17.97	0.75	0.19
[62]	SRF	20.60	NA	NA	9.39	NA	51.32*	7.36*	39.27*	1.64*	0.41*
[25]	Wood chips	15.3	NA	NA	2.52	NA	57.6*	7.4*	31.7*	2.4*	0.26*
[64]	Cardboard + potato	35.0	53.3	8.4	3.3	9000	51.2*	6.4*	42.2*	0.17*	0.03*
	MSW	46.5	25.5	8.0	20.0	7000	28.6	3.3	29.8	0	0
							60.39*	8.6*	28.3*	1.4*	0.06*

\*dry-ash-free (daf.); \*\*dry basis; NA: not available.

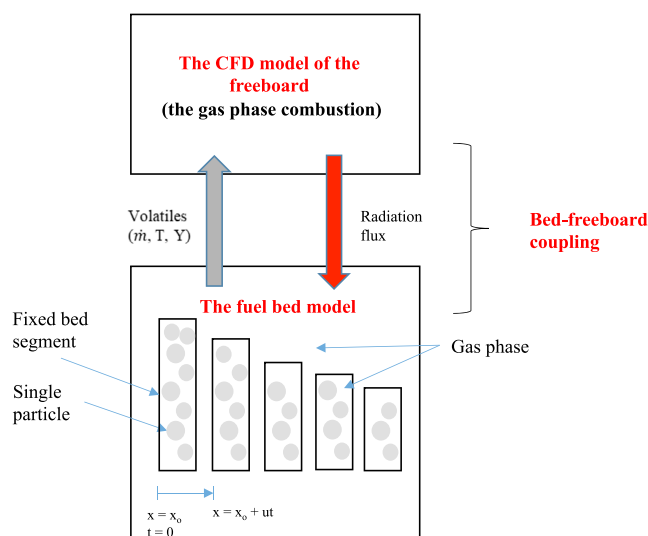


Fig. 3. The general modelling strategy for packed beds.

Besides the porosity and related gas permeability, the thermal conductivity and specific heat capacity of MSW components are poorly known. Most existing numerical models for MSW refer to studies of woody biomass, assuming that thermal conductivity and specific heat depend on temperature and solid composition. For biomass models, readers are referred to Haberle et al. [28] and Khodaei et al. [31]. In other MSW numerical studies, for plastics, the thermal conductivity was assumed 0.22 W/mK [73] or 0.2 W/mK [60,61], and the specific heat capacity was assumed 1500 J/kgK [60,61]. For organic, the thermal conductivity was assumed 0.2 W/mK [60] or 0.3 W/mK [61], and the specific heat capacity was assumed 2000 J/kgK [60,61].

### 3. Modelling approaches for packed beds

Fig. 3 illustrates the general modelling strategy for packed beds. Modelling the thermal degradation of a fuel bed involves gas and solid phase interaction at molecular, particle and bed level [74]. Furthermore, there is a strong interaction between the fuel bed and the freeboard region (i.e., the combustion chamber). Volatiles released from the fuel bed enter the combustion chamber and react with the oxygen in the injected air. This combustion of the volatiles produces heat which is transferred to the fuel bed by radiation, helping to initiate and sustain the thermal degradation of the solid phase. Overall, the modelling of solid fuel beds requires the characterisation of the solid-gas phase interaction, the solid degradation mechanism, and the fuel bed – freeboard coupling strategy.

This section starts with summarising different approaches for the modelling of packed beds with a focus on MSW applications. Next, the two main approaches for characterising particle – solid bed – gas interactions within a fuel bed are discussed, i.e., the continuous porous medium approach and the discrete phase approach (discrete phase modelling, DPM). A sub-section on the coupling between the fuel bed and the freeboard is also included. Sub-models on the conversion of MSW and other aspects of fuel bed modelling are discussed separately in Section 4 and 5, respectively.

#### 3.1. Classification of fuel bed models

In principle, the modelling approach for MSW packed beds is not different from that for coal and biomass packed beds. Classification of bed models, mainly in biomass applications, has been

conducted by several reviewers [29,31,32,75]. However, these classifications are somewhat random as they rely on different sets of criteria. Therefore, this paper clarifies how existing models can be uniformly grouped, focusing on MSW applications, as summarised in Table 3.

In general, classification of fuel bed models is based on four main aspects: 1) the applied discretisation method and governing equations [29,32,75], 2) the spatial treatment of the solid phase [29,31], 3) the coupling between the fuel bed and the freeboard [29,30,32] and 4) the dimensionality of the model [29].

##### 3.1.1. The discretisation method and governing equations

To begin with, two model types that do not involve discretisation of the packed bed are *empirical models* [66] and *thermochemical models* [76] (i.e., zero-dimensional models). For the former, the volatiles exiting the fuel bed are either determined experimentally or estimated from the elemental composition of the feedstock (i.e., semi-empirical models) [29]. For the latter, the fuel bed is considered as a perfect stirred reactor with a uniform distribution of concentration and temperature. Hence, the mixing and the heat and mass transfer can be neglected, and the thermal degradation of the solid bed can be described solely by thermodynamic equilibrium and chemical reaction kinetics [29]. These two approaches are well-accepted if the primary purpose of the fuel bed model is to provide gas-phase information for the CFD model of the freeboard. They are simple and yet can be accurate enough for a given specific system. Nonetheless, the accuracy of these models are very dependant on the quality of the specific input data and assumptions and might not be suitable for optimisation of fuel beds [28,29].

Indeed, a fuel bed system requires a more detailed description of transport phenomena and chemical reactions. This has led to the development of more advanced numerical models which are based on solving the conservation laws of mass, momentum and energy in the form of partial differential equations (i.e. governing equations). In order to solve these equations, discretisation of the geometry of the fuel bed is required. The following models can be distinguished based on their discretisation method and governing equations involved.

*Step change model* [53,77]: The fuel bed is discretised into a finite number of cells, each of which contains five main components representing the volatile fraction, moisture fraction, fixed carbon fraction, ash fraction and gas space. The volume of each component is estimated based on thermochemical equilibrium and chemical reaction kinetics. The solid phase composition and temperature are calculated based on the conservation of mass and energy.

*1D+1D model* [85]: Similar to the well-stirred reactor model, the packed bed is represented by vertically arranged layers. In each layer, however, one representative particle is chosen and discretised in the radial direction. Continuity, momentum, energy and species equations of the gas phase are solved on both particle and bed levels; and the thermal conversion of solid fuel and its mass conservation are described on the particle level.

*Well-stirred reactor model* [62]: The packed bed is divided vertically into layers having a thickness equal to one particle diameter. Each layer represents a well-stirred reactor with uniform temperature and composition profiles. The chemical reaction kinetics are solved for each layer while the heat and mass transport equations are solved amongst neighbouring layers.

*Finite volume (FV) method*: The fuel bed is divided into finite small sub-volumes where the partial differential equations, including mass and momentum conservation, species transport and energy conservation, are reformulated into a set of linear algebraic equations [30]. These equations are solved numerically over the entire computational domain in an iterative manner. Typically, a fuel bed is treated as an agglomeration of a finite number of solid



**Table 3**  
Documented fuel bed models for MSW.

Author & year	Bed type	Scale	Feedstock	Methodology	Dimension	Separate model?	Solid-gas thermal equilibrium	Shrinkage	Solid movement	Channelling	Coupling with freeboard	Validation	Sub-models
<i>Continuous porous medium models</i>													
Shin & Choi (2000) [78]	Fixed/ Moving beds	Lab.	Simulated waste	FV method	1D	Yes	Non-thermal equi.	x	–	–	–	x	–
Ryu et al. (2001) [54]	Fixed/ Moving beds	Lab.	Pinewood	FV method	1D	Yes	Non-thermal equi.	NA	–	–	–	x	Fuel mixing
Goh et al. (2001) [53]	Fixed bed reactor	Lab.	Simulated waste	Step change model	1D	Yes	Non-thermal equi.	x	–	–	–	x	–
Ryu et al. (2002) [79]	Moving bed	Industrial	MSW	–	2D	Yes	Non-thermal equi.	–	–	–	x	–	–
Yang et al. (2000) [55]	Fixed/ Moving beds	Lab.	Simulated waste	FLIC model	2D	Yes	Non-thermal equi.	–	x	–	–	x	–
Ryu et al. (2004) [58]	Martin-type moving grate	Industrial	Local MSW	FLIC model	2D	Yes	Non-thermal equi.	–	x	–	x	x	–
Salvador et al. (2008) [73]	A standard calorimeter cone	Lab.	Cardboard + PE	–	1D	Yes	Thermal equi.	–	–	–	–	x	–
Ismail et al. (2014) [80]	Martin-type moving grate	Industrial	MSW	Euler-Granular Multiphase model	2D	Yes	Non-thermal equi.	x	–	–	x	x	–
Sun et al. (2015a) [57]	Fixed/ Moving beds	Lab.	Simulated waste	Euler-Granular Multiphase model	2D	Yes	Non-thermal equi.	x	–	–	–	x	NO <sub>x</sub>
Sun et al. (2015b) [56]	1-D bench combustion test rig + moving bed	Lab.	Simulated waste	Euler-Granular Multiphase model	2D	Yes	Non-thermal equi.	x	–	–	–	x	NO <sub>x</sub> + Dioxin
Gu et al. (2019) [25]	Packed bed rig/moving bed	Lab.	Cardboard + potatoes	BASIC code	1D	Yes	Thermal equi.	x	–	–	–	x	–
Lai & Law (2019) [81]	Moving bed	Lab.	Simulated waste	1D Lagrangian approach (bed)	1D	Yes	Non-thermal equi.	–	–	–	–	x	–
Xia et al. (2020) [64]	Moving bed	Industrial	MSW	Granular flow	3D	No	Non-thermal equi.	x	x	–	x	x	–
<i>Discrete phase models</i>													
Simsek et al. (2009) [63]	Forward acting grate	Lab.	Waste	In-house DEM (LEATs code)	2D	Yes	Non-thermal equi.	x	x	–	x	–	–
Brosch et al. (2014) [61]	Fixed bed/ reciprocating grate / forward acting grate	Lab. / Industrial	Beech wood / MSW	In-house DEM model	2D	Yes	Non-thermal equi.	x	x	–	x	x	–
Kuwagi et al. (2016) [65]	Small incinerator	Pilot	Waste	Coupling DEM-CFD	3D	No	Non-thermal equi.	x	x	–	x	x	–
Wissing et al. (2017) [60]	Common grate systems	Industrial	MSW	In-house DEM model	3D	Yes	Non-thermal equi.	x	x	–	x	x	–

(continued on next page)

Table 3 (continued)

Author & year	Bed type	Scale	Feedstock	Methodology	Dimension	Separate model?	Solid-gas thermal equilibrium	Shrinkage	Solid movement	Channelling	Coupling with freeboard	Validation	Sub-models
<i>Other Models</i>													
Yang et al., 2001 [72]	Moving packed bed	Industrial	Local MSW	Stochastic model	NA	Yes	NA	-	-	X	-	X	-
Nakamura et al. (2003) [82]	Martin reverse acting grate	Industrial	MSW	Stochastic model	2D	Yes	NA	-	-	X	-	-	-
Frey et al. (2003) [66]	Moving bed	Pilot	MSW + RDF	Empirical model	-	NA	-	-	-	-	X	-	-
Yang et al. (2005) [83]	Moving bed	Industrial	Local MSW	Diffusion model + FLIC	NA	Yes	Non-thermal equi.	-	X	-	X	-	-
Huai et al. (2008) [84]	Two-stage reciprocating incinerator	Industrial	MSW	Semi-empirical model	0D	Yes	-	-	-	-	X	-	-
Matzing et al. (2018) [62]	Fixed bed / moving bed	Lab./Pilot/Industrial	Wood chip / SRF / MSW	Reactor cascade model (KLEAA code)	1D	Yes	Non-thermal equi.	X	-	-	X	X	-

NA: not applicable and / or not available.

particles. The thermal conversion of solid particles and their properties can be modelled in two ways corresponding to the so-called continuous porous medium approach and the DPM approach. More details on these approaches are given in sub-Sections 3.2 and 3.3.

### 3.1.2. The spatial treatment of the solid phase in the bed model

Depending on whether intra- and inter-particle phenomena are included, fuel bed models can be classified into two main types: continuous porous medium and particle resolved models [31].

In continuous porous medium models (i.e., heterogeneous models with a continuous phase), a fuel bed is regarded as a macroscopically homogeneous porous medium. For the sake of simplicity, the inter- and intra-particle phenomena are usually not considered [31]. Some studies [64,80], however, include the inter-particle interaction by employing the kinetic theory of granular flow to describe the solid phase.

In particle-resolved models (i.e., heterogeneous models with a non-continuous solid phase), a fuel bed is simulated as an aggregate of a finite number of individual fuel particles. These models not only include the interaction between particles but also take into account phenomena such as heat and concentration gradients inside the particle [31,86]. *1D+1D models* [85] and *DPM*, which are discussed in Section 3.1.1, belong to this category.

### 3.1.3. The coupling between the fuel bed and the freeboard

Fuel bed models can be categorised based on the degree of coupling between fuel bed and freeboard. The coupling degree is determined by the type of data that are shared and how they are interchanged [87]. A separate bed model (i.e., stand-alone bed model) can have one-way or two-way coupling with the freeboard, while a fully coupled model does not require a separate coupling strategy. *One-way coupling* applies when bed models (including empirical models) are used primarily to provide the mass fluxes of gas species and the gas temperature as the inlet conditions for the freeboard modelling [87]. In addition to these data, the more interactive *two-way coupling* involves information on the incident radiation flux from the freeboard model as input boundary conditions for the fuel bed. In a *fully coupled model*, the solid phase simulation is coupled directly to the CFD code of the gas phase, and both phases are resolved simultaneously. This approach can be applied for both DPM [65] and continuous porous medium models [64,88–90].

### 3.1.4. The dimensionality

The geometry of fuel beds can be presented fully three dimensional (3D) or simplified to two (2D) or even one (1D) dimension. A fuel bed is transient in three dimensions, but many studies have applied 2D or 1D calculations because of the constraint on computational resources [29].

## 3.2. Continuous porous medium approach

### 3.2.1. The fluid dynamic incinerator code (the FLIC model)

Over the last two decades, the continuous porous medium approach has been widely used to model MSW packed beds. Around the year 2000, a research group at the University of Sheffield (SUWIC) started developing an MSW bed model, initially as a step change model [53]. They eventually adopted the continuum porous medium approach and developed the so-called FLIC model [55]. In the next step in 2004, they adopted the combined simulation method developed by the Korea Advanced Institute of Science and Technology (KAIST) [54,78,79] to improve the accuracy of the model and to expand the research domain [58]. In 2005, they made an effort to capture the particle mixing by developing a diffusion model [83]. Afterwards, the FLIC model was used by SUWIC to investigate specific phenomena in grate-firing systems such as

$\text{NO}_x$  and PCDD/F formation, and to assess the effect of primary air flow rate, grate mixing, and feedstock properties (e.g., moisture content, particle size, density) on the combustion characteristics [68]. Since 2008, there has been no published evidence of further development of the model. Notwithstanding, some researchers [91–94] have still been using the FLIC model in combination with CFD simulations to study solid combustion processes.

The FLIC model simulates a moving bed as a continuous porous medium consisting of a gas and a solid phase. The equations of the solid phase are similar to those of the fluid phase [75] which are the continuity, momentum, energy and species equation.

Continuity equation:

$$\frac{\partial \rho_{sb}}{\partial t} + \nabla \cdot (\rho_{sb}(u_s - u_B)) = S_s \quad (1)$$

Momentum equation:

$$\frac{\partial \rho_{sb} u_s}{\partial t} + \nabla \cdot (\rho_{sb}(u_s - u_B)u_s) = -\nabla \cdot \sigma - \nabla \cdot \tau + \rho_{sb}g + A \quad (2)$$

Energy equation:

$$\frac{\partial \rho_{sb} H_s}{\partial t} + \nabla \cdot (\rho_{sb}(u_s - u_B)H_s) = \nabla \cdot (k_{eff} \nabla \cdot T_s) + \nabla \cdot q_r + Q_{sh} \quad (3)$$

Species equation:

$$\frac{\partial \rho_{sb} Y_{is}}{\partial t} + \nabla \cdot (\rho_{sb}(u_s - u_B)Y_{is}) = \nabla \cdot (D_s \nabla \cdot (\rho_{sb} Y_{is})) + S_{is} \quad (4)$$

where  $u_B$  and  $u_s$  are the horizontal velocity of the bed and average velocity of solid particles;  $S_s$  and  $S_{is}$  are source terms due to chemical reactions;  $q_r$  represents the heat by the radiation, and  $Q_{sh}$  represents the heat transfer between the gas and solid phases plus the heat generated by heterogeneous reactions. Term  $A$  accounts for random movement of particles (mixing) caused by mechanical disturbances of the moving grate and other random sources [83].  $D_s$  is the particle diffusion coefficient, which is an empirical value dependant on the physical properties of the MSW, grate type and operation conditions of the furnace.

Despite the popularity of the FLIC model, many problems have remained unsolved since 2008. Firstly, the model oversimplifies the reaction kinetics despite the complex composition of MSW [25]. In the FLIC model, the pyrolysis of MSW follows a one-step global mechanism, resulting in a predefined released volatiles composition without considering the feedstock properties. Also, the complex combustion mechanism of the gas phase is reduced to a three-reaction model. Secondly, despite that SUWIC introduced the momentum equations for the solid phase, it is still not possible to solve the particle velocity due to the lack of proper models for the stress terms. Instead, the horizontal bed velocity is predefined, and the vertical particle velocity in the bed is obtained from the solid-phase continuity equation [55]. In the model, the particle diffusion coefficient is included to account for the solid mixing, yet there is a discrepancy between the model input and the coefficient determined from stochastic models [83]. Last but not least, the FLIC model fails to include channelling and non-zero-gradient boundary conditions for gaseous concentrations and temperature at the surface of the fuel bed [25,72]. To address two problems regarding reaction kinetics and boundary conditions, Gu et al. [25] have recently developed BASIC (Bulk Accumulated Solids Incineration Code). However, their model is one-dimensional and does not take into account the particle movement.

### 3.2.2. Euler-Granular multiphase approach

Ismail et al. [80] and Xia et al. [64] developed Eulerian-Granular multiphase models to study a packed bed of solid waste on a moving grate. In Eulerian multiphase models, the solid and gas phases are treated mathematically as interpenetrating continua and are coupled via the pressure and interphase exchange coefficients [95].

The motion of the solid particles follows the kinetic theory of granular flow, which is based on an analogy between random particle motion arising from particle-particle collisions and thermal motion of molecules in a gas [80]. In this way, the momentum equation of the solid phase is written as [80]:

$$\frac{\partial((1-\phi)\rho_s u_s)}{\partial t} + \nabla \cdot ((1-\phi)\rho_s u_s u_s) = -(1-\phi)\nabla \cdot P_s + (1-\phi)\rho_s g - \beta(u_g - u_s) + \nabla \cdot ((1-\phi)\tau_s) \quad (5)$$

where  $\beta$  is the gas-solid interphase drag;  $P_s$  is the solid pressure which is estimated from the collision and kinetic terms as:

$$P_s = (1-\phi)\rho_s \Theta_s + 2(1+e)(1-\phi)^2 g_0 \rho_s \Theta_s \quad (6)$$

where  $\Theta_s$  is the granular pseudo-temperature;  $e$  is the coefficient of restitution of particle collisions;  $g_0$  is the radial distribution function of the solid phase [64,80].

The developed models show good validation with some experimental data from the literature [80] and measurements from a benchmark MSW incinerator [64]. These models were further employed to study the influence of MSW properties (i.e., moisture and ash content, particle size) [56,57,96] and waste throughput [64] on combustion characteristics.

Nevertheless, it is important to mention that the kinetic theory of granular flow has been widely used to simulate fluidised beds in which the moving particles are in constant motion and well spread. However, in a moving grate, particle movements are intermittent due to the periodical intervention of the grate stoking mechanism. Therefore, it is debatable whether this theory is suitable for modelling the combustion of MSW packed beds on grates in which mechanisms related to aggregation and bed collapse are of utmost relevance.

### 3.3. Discrete phase modelling

#### 3.3.1. General

Discrete phase models compute the motion of solid particles based on forces that apply on the particle such as drag force  $\vec{F}_{drag}$ , gravitational force  $\vec{F}_{gravitational}$  and other forces  $\vec{F}_{other}$ . The  $\vec{F}_{other}$  term represents the forces that result from the collision of the particles, which can be implemented using the Discrete Element Method (DEM) approach based on Cundall and Strack [97]. The position of the particle, at any moment, is tracked with respect to the Lagrangian reference frame. Generally, the governing equation of particle motion is written as [95]:

$$m_p \frac{d\vec{u}_p}{dt} = \vec{F}_{drag} + \vec{F}_{gravitational} + \vec{F}_{other} \quad (7)$$

Despite the high computational demand, the DPM approach has recently received much attention in solid fuel applications for two reasons. Firstly, it allows detailed modelling of individual particles as their internal gradients of temperature and species concentration can be straightforwardly implemented. Secondly, DPM can, to some extent, handle the particle movement on a moving grate [29,30]. In this light, DPM is a promising approach for woody biomass applications where particles are usually homogeneous in size, shape and composition.

For MSW applications, however, the applicability of DPM remains debatable because MSW particles show a wide variety in composition, size and shape. As a consequence, the imposed forces are hard to be estimated accurately at a reasonable computational cost. In this light, some research groups have attempted to tackle the complexity and variety of MSW in different ways. Wissing et al. [60] included cohesive and adhesive forces to account for the sticky behaviour and geometrical interlocking. For simplicity, the shape of particles is assumed spherical, and they belong to four size classes. Simsek et al. [63] introduced additional torques

to the rolling movement of particles in order to accommodate the effect of complex geometries. However, this study is still limited to so-called “representative” spheres. Kuwagi et al. [98] introduced a representative particle model (or similar particle assembly, SPA) in which particles with similar diameter, density and chemical composition are represented as one large particle. These particles are connected by cohesive forces and are treated as a lump. The interaction between particle lumps is calculated using the conventional DEM method.

### 3.3.2. Particle modelling

DPM requires a sub-model for simulating individual particles. Over the last two decades, numerous micro-level particle models have been developed for coal and biomass [27,28]. Based on the thermal regime, they are classified mainly into models for thermally-thin and thermally-thick particles. The thermal regime of particles is commonly determined using three dimensionless numbers, i.e., the thermal Biot number and two Pyrolysis numbers  $Py$  and  $Py'$ . The Biot number defines the ratio between the heat transfer resistance inside and at the surface of a particle. The pyrolysis numbers are the ratios of the reaction time to the heat transfer time ( $Py$  relates to the internal heat transfer and  $Py'$  relates to the external heat transfer). A low Biot number ( $Bi \ll 1$ ) defines a thermally thin regime, meaning that the temperature gradient inside a particle can be neglected. With high  $Py'$  and low  $Bi$  numbers, the chemical reaction is the controlling process, and a pure kinetic regime is obtained. High  $Bi$  and low  $Py$  numbers correspond to a thermal wave regime in which the internal heat transfer controls the thermal conversion process. The most complicated thermal regime is the thermally thick regime (high  $Bi$  and high  $Py$  numbers) whereby the internal heat transfer and kinetics are strongly coupled [74,99,100].

Not all existing particle models can be applied to simulate a solid bed because the computational cost can be too high. For this reason, a single particle is often modelled as thermally thin [63]. However, research has shown that biomass particles in grate-firing applications are mm-sized and often behave as thermally-thick [32,100,101]. As mentioned in Section 2.2, MSW components can be up to a few centimetres in size and thus, they also behave as thermally-thick. Therefore, it is necessary to include the effect of temperature and concentration gradients inside MSW particles.

Thermally thick particle models have been reviewed comprehensively by Haberle et al. [28], focusing on biomass applications. The layer model (or interface-based model or front-based model) proves most relevant to grate-firing applications and has been applied to the MSW model of Wissing et al. [60]. In this model, a particle is represented by four dynamic layers, i.e., wet wood, dry wood, char and ash. The primary assumption of the model is that the intra-particle diffusion of heat and mass is much slower than the chemical reaction and phase change rates. Hence, only the energy and mass equations are solved to model the development of the four layers. By limiting the number of governing equations and allowing coarse spatial discretisation, the computational cost is reasonably low [28].

## 3.4. Coupling between the fuel bed and the freeboard

### 3.4.1. CFD models of the freeboard

The modelling of the gas phase in the freeboard has been discussed thoroughly in other work [29,32]. In summary, a comprehensive CFD model of the freeboard requires four sub-models to describe the turbulent mixing of gases, the reaction scheme, the interaction between chemical reactions and mixing (i.e., combustion models), and the heat transfer by radiation. In combustion furnaces, the turbulent flow of the gas phase is usually modelled by RANS (i.e., Reynolds-averaged Navier-Stokes equations), thanks

to its low computational cost. The choice of turbulence models for RANS simulations, however, is not obvious. It depends largely on the given geometry, the flow regime and other sub-models [29]. For gas-phase reaction mechanisms, global one- or two-step mechanisms seem more practical than detailed mechanisms. The detailed reaction models can enhance the accuracy and allow simulations of pollutant formation, but they slow down simulations significantly due to a large number of species and reactions. For combustion modelling, the Eddy break-up model has been widely used. This model assumes infinitely fast reactions and estimates the combustion velocity based on the turbulent mixing rate. For the radiative heat transfer, the Discrete Ordinates (DO) and the P-1 radiation models are the most commonly-used methods. The DO model comprises a number of radiative transfer equations (RTE) for different discrete solid angles while the P-1 model simplifies the RTEs to an elliptical partial differential equation. The P-1 model consumes less computational resources than the DO model, but it tends to overpredict the radiative heat flux [29].

### 3.4.2. Coupling between the fuel bed and the freeboard

The interaction between fuel bed and freeboard is dynamic. The combustion in the freeboard is strongly dependant on the composition, temperature, and flow rate of the volatiles yielding from the fuel bed. The thermal conversion of the fuel bed, on its turn, relies on the heat flux from the freeboard. For the sake of simplicity, some studies [62,80] neglected the dynamics of radiation heat fluxes and only used results from the fuel bed model to set boundary conditions for the freeboard. This one-way coupling might be satisfactory when the focus is on the freeboard modelling, but for studies on combustion furnaces as a whole, two-way coupling or full coupling is the appropriate method.

Full coupling between the fuel bed and the freeboard was obtained in some studies using the CFD-DEM approach [65] or the CFD-Eulerian multiphase approach [64,88–90]. The gas flow in the fuel bed and the freeboard are solved using the same mathematical procedure. The thermal conversion and the movement of the solid phase are strongly coupled to the gas phase; in this way, they are solved at the same time. Although the full coupling simulation can yield more accurate results than separate bed/freeboard modelling, it demands a high computational capacity and might be numerically unstable.

A separate model handling the two-way coupling (or bidirectional coupling) might be more pragmatic than the fully-coupled models for two reasons. Firstly, the difference in time scale between the heterogeneous reactions within the fuel bed and the homogeneous reactions in the freeboard suggests that bed modelling should be conducted transiently while the flow field in the freeboard region can be resolved in a steady-state [60,61]. Secondly, separate modelling can reduce computational demand and somehow helps to avoid instability. Furthermore, it also allows more flexibility within the separate solid and gas phase simulations.

On the other hand, two-way coupling introduces some calculation errors due to the mismatch in time scale and dimension between the fuel bed and freeboard models. For the former, since the fuel bed simulation is transient and the freeboard simulation is steady-state, it is necessary to define a suitable time interval to exchange data so that the CFD model has sufficient time to converge [63]. A possible suitable time interval can be, e.g., the duration of one feeding cycle of the waste feeder [60]. The fuel bed model is often one- or two-dimensional while the freeboard model is three-dimensional. Therefore, it is compulsory to perform spatial extrapolation over the grate width [61]. For example, Matzing et al. [62] split the surface of the waste bed into several rectangular segments and used the volume-averaged gas velocity, concentration and temperature as inputs for the freeboard model. Another disadvantage of the two-way coupling approach is that the location of



the interface is not clearly defined, possibly causing loss of data at the boundary. Commonly, the interface between the fuel bed and the freeboard is assumed to be placed above the bed surface. This assumption might lead to some loss of accuracy because a part of gas-phase combustion is solved by the fuel bed model rather than by the freeboard CFD solver [87]. Additionally, since it is difficult to obtain experimental data at the bed freeboard interface, the validation of bed models is challenging [28].

Given the trade-off between accuracy, flexibility and computational cost of the fuel bed model, the two-way coupling approach has still been favoured in many studies [60,61,63,79,83]. The general coupling strategy was first introduced by Ryu et al. [79]. Basically, the mathematical algorithm for two-way coupling requires three steps, i.e., data import and export, extrapolation and interpolation, and convergence check [102]. Data of volatiles generated by the bed model, consisting of mass flow, composition, density and temperature, are exported, extrapolated, and used as boundary conditions for the CFD freeboard model. The results of the CFD freeboard model (i.e., the radiation fluxes), on their turn, are introduced to the bed model as a boundary condition on the surface of the bed. The two models are simulated, and data are exchanged iteratively until converged solutions are obtained for both fuel bed and freeboard [63,79,102].

#### 4. Sub-models for the thermal conversion processes of MSW

##### 4.1. Drying

Given that MSW can constitute up to more than 50 wt.% of moisture (see Section 2), the moisture evaporation plays a crucial role in the overall MSW thermal conversion process. It affects, e.g., energy recovery efficiency, ignition rate, conversion time, and burning degree. The high moisture content of MSW is not only due to the presence of MSW fractions with high moisture content (e.g., food and garden waste) but also due to water that enters during storage and collection (e.g., rainwater). The majority of the moisture is present in the form of free water liquid in the voids of the waste bed and bound water in the solid structure of MSW components; there is also a negligible amount of water vapour present in the pores [30,31].

The moisture evaporation process of biomass and MSW share a number of key features, which have already been discussed in detail in other work [29–31]. Concretely, there are three main approaches for modelling the moisture evaporation: the thermal approach (i.e., the heat sink model), the kinetic rate model (i.e., the Arrhenius model), and the equilibrium model (i.e., the diffusion model).

*The heat sink model* considers that the evaporation process is thermally controlled and only starts when the temperature reaches the boiling point. Due to its simplicity, the heat sink model has been adopted in several MSW models [60,87]. The key problem of the heat sink model is that it neglects the drying process at temperatures below the boiling point and overlooks the diffusion of bound water. In addition, this approach often causes numerical instability due to the step function around the boiling point [30].

*The kinetic rate model* considers the drying process as a chemical reaction [73,81]. Hence, its implementation is straightforward, and the model can afford high computational stability. However, Arrhenius parameters, which are needed to estimate the drying rate, cannot be universally determined and as such, the applicability of the model is limited.

*The diffusion model* is based on the thermodynamic equilibrium between the liquid and vapour phases [78]. This approach is valid for low-temperature processes [28,31] and is often

combined with the heat sink model to cover a broad range of temperatures [25,53,55,62,64].

For the sake of simplicity, most models do not take into account the effect of solid shrinkage during the drying process. Chen et al. [103] conducted an experimental study in combination with a numerical model to prove the relevance of this effect. Using the diffusion approach, they included the shrinkage velocity when solving the moisture mass and energy conservation equations by means of the finite-difference method. They obtained a fair correspondence between numerical and experimental results.

##### 4.2. Pyrolysis

###### 4.2.1. Thermal analysis of MSW

MSW is a mixture of various fractions with different thermal degradation behaviours. As already discussed in Section 2, the combustible fraction of MSW can be regarded as a mixture of lignocellulosic materials (i.e., containing cellulose, hemicellulose, and lignin), plastics, and some other materials such as rubber/tyres and low stability organic components. Thermogravimetric analysis (TGA) is the most commonly used method to study the decomposition behaviour of MSW. According to TGA studies, the decomposition of MSW can take place in two to five stages [44,47,51,52,104,105]. The two major stages correspond to the devolatilisation of the cellulosic and hemicellulosic fraction (250 – 400 °C) and of the chlorine-free plastics (350 – 500 °C) [51]. These two stages also overlap with the degradation of PVC [51,104]. In some studies, the decomposition of lignin and protein is considered as a separate stage between 360 and 455 °C [47,104,105]. Two other stages apply to the decomposition of for low stability organic components (mainly starch) at 300 °C and inorganics at temperatures well above 600 °C [52,104]. Rubber shows a quite complicated thermal behaviour as it decomposes typically through three stages at 190 – 310 °C, 310 – 429 °C and 577 – 660 °C, respectively [47].

###### 4.2.2. Kinetic modelling using thermal analysis data

A kinetic study of multi-component solid fuels (e.g., biomass or waste) is necessary to understand their thermal behaviour and to predict reaction mechanisms and rates. For pyrolysis at atmospheric pressure, as is the case for waste that is thermally treated in an incinerator, the reaction rate is generally expressed as a function of temperature  $T$  and the extent of conversion  $\alpha$  as follows [106]:

$$\frac{d\alpha}{dt} = A \exp\left(-\frac{E}{RT}\right) f(\alpha) \quad (8)$$

A complete kinetic study requires the determination of the activation energy  $E$ , the pre-exponential factor  $A$  and the reaction model function  $f(\alpha)$ . In the literature, these parameters are often determined by TGA via the model-fitting or model-free isoconversional methods [106]. *The model-fitting method* assumes that the thermal decomposition of a single component can be described as a first or  $n^{\text{th}}$ - order reaction (i.e.,  $f(\alpha) = (1 - \alpha)^n$ ,  $n = 1$  or  $n \neq 1$ ). The order-based mechanism and the distributed activation energy model (DAEM) belong to this category. The DAEM considers that every reaction of a component is a combination of infinite first-order reactions and that the activation energies for these reactions follow a continuous distribution function. In contrast, *the model-free method* can determine the activation energy as a function of the conversion degree without having to assume the reaction model  $f(\alpha)$ . Flynn-Wall-Ozawa (FWO), Friedman, and Kissinger-Akahira-Sunose (KAS) are the most popular model-free analysis methods in MSW applications. The decomposition mechanism, even though it cannot be provided using this method, can be determined using master plots [107].

**Table 4**  
Pyrolysis mechanisms applied to lignocellulosic materials [29,31].

	One-step global mechanism model	Multi-component single mechanism	One-component competitive mechanism	Detailed mechanism
Mechanism	$Biomass \rightarrow Char + Volatiles$	$Cellulose \rightarrow Volatiles + Char$ $Hemicellulose \rightarrow Volatiles + Char$ $Lignin \rightarrow Volatiles + Char$	$Biomass \rightarrow Volatiles$ $Biomass \rightarrow Tar$ $Biomass \rightarrow Char$ $Tar \rightarrow Volatiles$ $Tar \rightarrow Char$	Considering competitive and parallel reactions for multiple components, as well as secondary reactions and interactions between products
Rate expressions	$\frac{d\rho_{sb}}{dt} = -Ae^{-\frac{E}{RT}} \rho_{sb}$	$\frac{d\rho_{si}}{dt} = -Ae^{-\frac{E_i}{RT}} \rho_{si}$	$\frac{d\rho_{sb}}{dt} = -\rho_{sb} \sum_i A_i e^{-\frac{E_i}{RT}}$	
Applicability	Predicts mass loss rate, temperature effects are well-captured	Predicts mass loss rate	Predicts conversion rate and product yields when coupled with transport phenomena	
Advantages	Easy to implement	A more accurate description of the biomass devolatilisation curves; can apply to various biomass types	Has sufficient flexibility and accuracy in describing the pyrolysis process in biomass combustion	More comprehensive
Disadvantages	Cannot predict the yield variations, kinetic data is specific for each feedstock	Needs more input data, cannot include the interaction between components	Kinetic data are scattering; biomass as a reactant is not described in detail	Complicated, requires further advances and deeper understanding
Ref. (s)	[127,128]	[129]	[130–134]	[135,136]

Kinetic data have been determined for individual MSW fractions as well as for MSW mixtures. Because MSW is a complicated multi-component system with a high degree of heterogeneity, the most practical way to study its thermal degradation processes is to use a weighted sum of the kinetic data of the different fractions [44,108]. This approach offers vast flexibility as it is possible to cover a wide range of MSW compositions, but it completely neglects the synergetic effect amongst individual components [51,109–111]. On the other hand, dealing with MSW mixtures as one pseudo-fraction might be more straightforward than dealing with a mixture of several fractions.

Generally, the values for  $A$  and  $E$  obtained in different kinetic studies are extremely scattered and inconsistent, with differences up to several orders of magnitude. An explanation for this is that the kinetic data largely depend on materials, calculation methods (model-fitting or isoconversional methods) and conditions at which the TGA experiments are conducted (e.g., isothermal or dynamic, temperature, heating rate, apparatus or ambient conditions) [51,108]. Table 2 and Table 3 in the Supplementary Material present some published data from experimental studies on the kinetics of MSW pyrolysis (MSW fractions [51,52,108,110,112–116] and MSW as a mixture [40,47,52,105,108,112,117–124]). Nonetheless, the inconsistency of existing kinetic models and data makes it a great challenge to simulate the pyrolysis process accurately. Section 4.2.3 discusses how existing bed models tackle this issue and which challenges remain.

#### 4.2.3. Pyrolysis models

Most of the existing MSW bed models have adopted the pyrolysis models of biomass, assuming that MSW mainly consists of lignocellulosic materials. Pyrolysis models of woody biomass have been developed for decades and were reviewed thoroughly in other papers [27–29,31]. As shown in Table 4, there are four main pyrolysis mechanisms which can be classified based on two main presumptions: 1) whether biomass is considered as one pseudo-component or as a mixture of components (typically cellulose, hemicellulose and lignin); 2) whether the devolatilisation reaction of each component is considered a single reaction or a set of competitive reactions. This classification makes the one-step global mechanism the simplest and the detailed mechanism the most complicated model.

The one-step global mechanism has been widely used in the past because of its simplicity [25,63,65,79]. However, since this mechanism has its limitations regarding accuracy and flexibility, some other researches adopted the one-component competitive mechanism [54,78,81,125] or the detailed mechanism [62,126]. Secondary reactions, which involve the decomposition of tar to char and light gas at high temperatures, were included in some of these pyrolysis models [125]. For a detailed review of tar cracking reactions, readers are referred to the paper by Khodaei et al. [31].

Nevertheless, Section 2.1 has already pinpointed a need for including pyrolysis of plastics, possibly low stability organic components and rubber/tyres in MSW combustion modelling. Pyrolysis of plastics was only included in two studies on MSW bed modelling [62,73]. They both assumed PE as the default plastic species, with a devolatilisation reaction following first-order kinetics with  $A = 1.05E7 \text{ s}^{-1}$ ,  $E = 252.6 \text{ kJ/mol}$  [73] or  $A = 2E16 \text{ s}^{-1}$ ,  $E = 265 \text{ kJ/mol}$  [62].

In general, as can be inferred from Table 5, there is no consensus on which model is the most appropriate for the simulation of MSW pyrolysis. It is also important to note that there is considerable uncertainty on the heat of pyrolysis reactions, knowing that they tend to vary from endothermic to exothermic as conversion proceeds [28]. A decision on the most appropriate kinetics and thermodynamics of pyrolysis reactions remains a challenge as it is related to the available experimental data, the characterisation of the waste, the expected accuracy, the general model approach, and the computational affordability.

#### 4.2.4. Volatiles

The pyrolysis of MSW releases hundreds of species which can generally be categorised as either main gas components or inorganic volatiles. The main gas components consist of combustible gases (light and heavy hydrocarbons),  $O_2$ ,  $N_2$ ,  $CO$ ,  $CO_2$ , etc. The inorganic volatiles include S- and Cl- fractions, and heavy metal compounds (e.g., Pb, Zn, Cd, etc.). The amount of inorganic volatiles is relatively low, but they contain environmental pollutants such as chlorides and sulfur oxides. In addition, they are leading components in deposit formation [32]. Inorganic volatiles are often neglected when it comes to predicting combustion performances. When being considered, their concentration in the gas phase will be predominantly determined by the model used for the packed bed. In view of its scope, this paper further focuses on the main

**Table 5**  
Pyrolysis models in MSW fuel bed modelling.

Pyrolysis models	Pyrolysis reaction mechanism	Rate constants	Rate expressions	Heat of reactions	Ref. (s)	Scale
One-component competitive mechanism	Wood (oak) $\xrightarrow{k_1}$ Char Wood (oak) $\xrightarrow{k_2}$ Tar Wood (oak) $\xrightarrow{k_3}$ Gas	$A_{1-3} = 7.4\text{E}5; 4.12\text{E}6; 1.43 \text{E}4 \text{ s}^{-1}$ $E_{1-3} = 106.5; 112.7; 88.6 \text{ kJ/mol}$	$\frac{d\rho_{sb}}{dt} = -(k_1 + k_2 + k_3)\rho_{sb}$	–	[27,128,134]	Particle level
One-component competitive mechanism	Wood (hard wood) $\xrightarrow{k_1}$ Gas Wood (hard wood) $\xrightarrow{k_2}$ Tar	$k = k_1 + k_2 = 33.38 \times 10^4 e^{-\frac{8299}{T}}$	$\frac{dY_{vol}}{dt} = k(Y_{vol,\infty} - Y_{vol})$ $Y_{vol,\infty} = 0.93$	–	[27,128,148]	Particle level
Multi-component competitive mechanism	Cellulose $\xrightarrow{k_1}$ Charcoal, $\text{CO}_2$ , $\text{CO}$ , $\text{H}_2\text{O}$ Cellulose $\xrightarrow{k_2}$ Tar Cellulose $\xrightarrow{k_3}$ Levoglucosan	$A_1 = 2\text{E}3 - 3\text{E}3 \text{ s}^{-1}$ $E_1 = 6.6\text{E}4 - 6.9\text{E}4 \text{ J/mol}$	$\frac{d\rho_{sb}}{dt} = -k(\rho_{sb} - \rho_{sb,\infty})$	–210 to 0 J/g	[64,99,128]	Particle level
One-step global mechanism	Wood $\rightarrow$ Volatiles	$A = 4.2\text{E}6 \text{ min}^{-1}$ $E = 83 \text{ kJ/mol}$	–	–	[128,149]	Particle level
One-component competitive mechanism	Almond shells $\xrightarrow{k_1}$ Char Almond shells $\xrightarrow{k_2}$ Tar Almond shells $\xrightarrow{k_3}$ Gas	$A_{1-3} = 2.98\text{E}3; 5.85\text{E}6; 1.52\text{E}7 \text{ s}^{-1}$ $E_{1-3} = 73; 119; 139 \text{ kJ/mol}$	$\frac{d\rho_{sb}}{dt} = -(k_1 + k_2 + k_3)\rho_{sb}$	–	[27,125,132]	Particle level
One-component competitive mechanism	Wood $\xrightarrow{k_1}$ Volatiles Wood $\xrightarrow{k_2}$ Char	$k_1 = 5.16 \times 10^6 e^{-\frac{10,700}{T}}$ $k_2 = 2.66 \times 10^{10} e^{-\frac{12,800}{T}}$	$\frac{dm_{vol}}{dt} (\frac{\text{kg}}{\text{s}}) = k_1 m_{wood}$ $\frac{dm_{char}}{dt} (\frac{\text{kg}}{\text{s}}) = k_2 m_{wood}$	–418 kJ/kg –418 kJ/kg	[54,78,81,125]	Bed level
One-step global mechanism	Volatilmatter(s) $\rightarrow$ Volatiles(g)	$k = 1.5 \times 10^8 e^{-\frac{15,105}{T}}$	$\frac{dm_{vol}}{dt} (\frac{\text{kg}}{\text{m}^3 \text{s}}) = -(1 - \phi)k\rho_s Y_{vol}$	NA	[79]	Bed level
DAEM model	Waste $\rightarrow$ Volatiles + Char	$A = 3.2\text{E}9 \text{ s}^{-1}$ ; $E_0 = 203 \text{ kJ/mol}$ ; $\sigma = 32.96 \text{ kJ/mol}$	$\frac{dY_{vol}}{dt} = -k(Y_{vol} - Y_{vol,\infty})$	NA	[55]	Bed level
One-step global reaction	Waste $\rightarrow$ Volatiles + Char	$A = 5.16\text{E}6 / 3.4\text{E}4 / 7\text{E}4 / 3\text{E}3 / 2.98 \text{E}3 \text{ s}^{-1}$ $E = 84 / 69 / 83 / 69 / 73.1 \text{ kJ/mol}$	$\frac{dY_{vol}}{dt} = k(Y_{vol,\infty} - Y_{vol})$	NA	[128]	Bed level
Detailed mechanism	$\text{C} \xrightarrow{k_1} 0.3871 \text{ I} + 0.6129 \text{ VM}$ $0.3871 \text{ I} \xrightarrow{k_2} 0.3258 \text{ Char} + 0.0613 \text{ VM}$ $\text{PE} \xrightarrow{k_{PE}} \text{C}_2\text{H}_4$ C: cardboard; I: intermediate; VM: volatile matter	$k_1 = 1.81 \times 10^{10} e^{-\frac{15,137}{T}}$ $k_2 = 20,374 e^{-\frac{8951}{T}} k_{PE} = 1.05 \times 10^{17} e^{-\frac{30,382.5}{T}}$	$\frac{dm_c}{dt} (\frac{\text{kg}}{\text{s}}) = -k_1 m_c$ $\frac{dm_i}{dt} (\frac{\text{kg}}{\text{s}}) = -0.3781(k_1 m_c - k_2 m_i)$ $\frac{dm_{char}}{dt} (\frac{\text{kg}}{\text{s}}) = -0.3258 k_2 m_i$ $\frac{d\rho_{PE}}{dt} (\frac{\text{kg}}{\text{m}^3 \text{s}}) = -k_{PE} \rho_{PE}$	–0.142; –0.455; –1.21 MJ/kg	[73]	Bed level
One-step global mechanism	$v_f \text{ Fuel} \rightarrow v_{vol} \text{ Volatiles} + v_{char} \text{ Char}$ $v$ : stoichiometry coefficients	$A = 0.112 \text{ s}^{-1}$ $E = 20,000 \text{ J/kg}$	$\frac{dm_{volatile}}{dt} (\frac{\text{kg}}{\text{s}}) = -k m_{volatile}$	NA	[63]	Particle level
One-step global mechanism	Fuel $\rightarrow$ Volatiles(g)	$A = 3.63\text{E}4 \text{ s}^{-1}$ $E/R = 9340 \text{ K}$	$\frac{dm_{volatile}}{dt} (\frac{\text{kg}}{\text{m}^3 \text{s}}) = k\rho_{sb} Y_{volatile}$	NA	[44,80]	Bed level
One-step global mechanism	Pyrolyzed material (s) $\rightarrow$ $\text{CO(g)} + \text{CH}_{2.12}\text{O}_{0.87}\text{(g)} + \text{CH}_4\text{(g)} + \text{H}_2\text{(g)}$	$A = 10 \text{ s}^{-1}$ $E = 4.73 \text{E}7 \text{ J/mol}$	$\frac{dY}{dt} (\text{s}^{-1}) = -k(1 - Y)^{1.333}$	–628 kJ/kg	[65]	Particle level
Detailed mechanism	Cellulose $\text{C}_6\text{H}_{10}\text{O}_5 \xrightarrow{k_1} 0.5\text{CO}_2 + 2.5\text{CO} + 1.5\text{H}_2\text{O} + 0.5\text{CH}_4 + 2.5\text{H}_2 + 2.5\text{C}_{fix}$ Cellulose $\text{C}_6\text{H}_{10}\text{O}_5 \xrightarrow{k_2} 0.125\text{CO}_2 + 0.625\text{CO} + 0.375\text{H}_2\text{O} + 0.125\text{CH}_4 + 0.625\text{H}_2 + 0.625\text{C}_{fix} + 0.75 \text{ tar } \text{C}_6\text{H}_{10}\text{O}_5$ Hemicellulose $\text{C}_5\text{H}_8\text{O}_4 \xrightarrow{k_3} 0.5\text{CO}_2 + 2\text{CO} + \text{H}_2\text{O} + 0.5\text{CH}_4 + 2\text{H}_2 + 2\text{C}_{fix}$ Lignin $\text{C}_{10}\text{H}_{10}\text{O}_4 \xrightarrow{k_4} 0.75\text{CO}_2 + 2.5\text{CO} + 2.45\text{CH}_4 + 0.1\text{H}_2 + 4.3\text{C}_{fix}$ Tar $\text{C}_6\text{H}_{10}\text{O}_5 \xrightarrow{k_5} 1.5\text{CO}_2 + 2\text{CO} + 2.5\text{CH}_4$ ( $\text{C}_2\text{H}_4$ ) <sub>980</sub> $\xrightarrow{k_{PE}} 980 \text{ C}_2\text{H}_4$	$A_{1-5} = 2\text{E}8; 3\text{E}13; 1\text{E}7; 1.5\text{E}14; 2\text{E}7 \text{ s}^{-1}$ $E_{1-5} = 132; 195; 105; 192; 122 \text{ kJ/mol}$ $A_{PE} = 2\text{E}16 \text{ s}^{-1}$ $E_{PE} = 265 \text{ kJ/mol}$	–	NA	[62]	Particle level
One-step global mechanism	Dry MSW $\rightarrow$ Volatiles + Char	$A = 3.4\text{E}4 \text{ s}^{-1}$ $E = 6.9\text{E}7 \text{ J/kmol}$	$\frac{d\rho_{sb}}{dt} (\frac{\text{kg}}{\text{m}^3 \text{s}}) = -k\rho_{sb}$	Calculated	[25]	Bed level

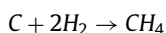
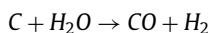
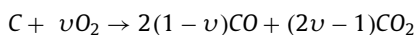
gas components, hereafter referred to as “volatiles”. The inorganic volatiles are briefly discussed in Section 7, which is more relevant to applications of fuel bed models and might be an important focus of future research in the field.

The main gas components are generally grouped into light gases (i.e., light hydrocarbons, CO, CO<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub>, etc.) and tar (i.e., heavy hydrocarbons) [29,74]. Because of the MSW heterogeneity, a complete characterisation of volatiles is challenging. In numerical modelling, the volatiles can be represented in various ways: as one single equivalent gas component (C<sub>x</sub>H<sub>y</sub> or C<sub>x</sub>H<sub>y</sub>O<sub>z</sub>) [55,78,80,128], as two single equivalent gas components (light gas and tar) [81] or as a mixture of gas components (CO, CO<sub>2</sub>, H<sub>2</sub>, C<sub>x</sub>H<sub>y</sub>, C<sub>x</sub>H<sub>y</sub>O<sub>z</sub>) [64,65,81]. For the sake of simplicity, the composition of these gases is commonly predefined regardless of the feedstock. This crude assumption was however avoided in recent studies [25,60,96,137], in which the composition of volatiles was estimated from the given proximate and ultimate analysis of the MSW feedstock based on the conservation of energy and chemical elements (e.g., based on Thunman et al. [138]). Apart from this, the dependency of released volatiles on the composition of the feedstock is intrinsically taken into account if the detailed mechanism is used for the pyrolysis modelling [62,126].

#### 4.3. Char gasification and oxidation

As reviewed in Section 2.1, dry MSW fractions contain up to 10 wt.% fixed carbon, which remains in the char during the pyrolysis process. In real applications, the char yield varies depending on the reaction temperature and the heating rate [27]. The subsequent combustion of char releases heat that helps to sustain the thermal degradation process, which is an important phenomenon in packed-bed combustion.

The conversion of char is a heterogeneous reaction between solid and gaseous reactants, typically taking place in three steps: transfer of gaseous reactants to the char surface, chemical reactions at the char active sites and diffusion of products away from the surface [31]. The most important reactions that occur on the char surface are given below:



The first reaction refers to the char oxidation, and the three following reactions are char gasification reactions.

The char conversion rate depends not only on chemical kinetics but also on the transport of reactants/products, either of which is the rate-limiting step. To this end, the concept of the effective rate constant ( $k_{global}$ ) was introduced [55,80,101,139], taking into account both the chemical kinetic and diffusion rate constants ( $k_r$  and  $k_d$ ). The rate of char conversion is generally written as [107]:

$$\frac{dm_{char}}{dt} = -k_{global}P_i^n S_a M_C \quad (9)$$

where  $P_i$  is the partial pressure of the gaseous compounds;  $n$  is the reaction order;  $S_a$  refers to the active surface of char.

In the literature, two main approaches have been applied to model the structural change of the solid phase during the reaction, i.e., the continuous model and the shrinking-unreacted-core model (i.e., SCM). The former assumes that gases can travel into the porous particle, and reactions can occur inside the solid structure.

Examples of continuous models are the volume reaction model, the random pore model and the grain model [140]. Amongst these, the random pore model (RPM) has recently gained some attention in biomass applications [28,141]. It assumes that heterogeneous reactions occur at the active sites inside the micropores of solid particles. At first, the active surface increases because of pore growth and then decreases due to the coalescence of neighbouring pores [107]. The SCM, on the other hand, assumes that reaction takes place initially at the outer skin of the particle and gradually progresses into the solid, leaving converted material and inert solid behind [107]. Although SCM presumes that the solid particle is non-porous, it can still represent the char conversion process realistically, especially in case the conversion is diffusion-limited [142]. Hence, SCM remains popular for the modelling of the char conversion process.

According to the applied model, the char burning rate is expressed either as the intrinsic chemical and pore diffusion rate [143] or as the global chemical and bulk diffusion rate [144]. In other words, the former (called the intrinsic reaction model) determines the conversion rate per unit surface area of the char. The latter (called the global reaction model), in contrast, estimates the overall rate of char conversion per unit mass using an “apparent” chemical reaction order [145]. The intrinsic reaction model requires a detailed description of char structural change during the conversion process, while the global reaction model only needs to simulate the change in the outer surface of the char.

Table 6 shows an overview of char oxidation and gasification models applied in modelling of solid fuel beds with a focus on MSW. It can be seen that there are three primary sources of uncertainty in the estimation of the char conversion rate, which are: reaction mechanism, rate expressions and char reactivity (i.e.,  $S_a$ ). Regarding the reaction mechanism, many studies only include the char oxidation reaction [25,32,63,73,78,80,81,128]. This assumption is acceptable mainly because the fixed carbon fraction in MSW and biomass is small [25], and the char oxidation reaction on the bed surface is faster than the gasification reactions [28–30]. However, one should note that gasification reactions are of relevance within the waste bed where solid particles are subject to oxygen-deficient conditions [32]. It is also not clear when, in practical applications, the critical oxygen mass fraction in the gas phase is reached so that gasification reactions can be assumed inconsequential [28]. Therefore, a model that can cover a broad range of operational conditions might require the implementation of both oxidation and gasification reactions.

## 5. Other processes and considerations in the modelling of thermal conversion of waste beds

### 5.1. Heat transfer

Heat transfer in a packed bed is a combination of three main mechanisms: convective heat transfer between solid and gas phases, heat conduction between solid bodies in contact and radiation. The molecular conduction of the gas phase is typically neglected as it has a minimal effect on the overall heat transfer [60,63].

#### 5.1.1. Convective heat transfer

The convective heat transfer between the solid and gas phases is included in most studies. Generally, the heat transfer coefficient is estimated using the Nusselt number, which can be calculated by the equation proposed by Wakao and Kaguei [146] [25,55,62,64,78], or by Ranz-Marshall [147] [65], or from empirical correlations [60,63]. Generally, the Nusselt number is determined as a function of the Reynolds number and the Prandtl





whereas the second term is a function of emissivity, particle size, bed porosity and temperature cubed [28,30,31]. To date, there has been little agreement on the exact description of these two terms. Likewise, there is no consensus on how to model the specific heat capacity based on solid composition and temperature.

Considering that the radiative thermal conductivity concept is still primitive, some authors [55,78,80] attempted to model radiation more accurately by solving detailed radiative heat transfer equations in absorbing, emitting and scattering media (e.g., two- and four-flux radiation models, the Rosseland model [150], the DO model or the P-1 model). The main challenge of this method regards the identification of the radiative properties and geometrical parameters [151], as well as the high computational requirement [31].

### 5.1.3. Modelling conductive and radiative heat transfer in DPM

The use of the effective thermal conductivity is not appropriate for discrete phase models. They require separate heat transfer models for conduction and radiation mechanisms. The particle-particle heat conduction has been described by different mechanisms, such as conduction through the gas lens [152] and direct conduction due to elastic deformation during impact [153,154]. Simsek et al. [63] and Wissing et al. [60] used the method by Vargas and McCarthy [153] who describe the direct contact heat transfer between particles as:

$$\dot{Q}_{pp} = \frac{1}{R_c} (T_{p,i} - T_{p,j}) \quad (11)$$

where  $T_{p,i}$  and  $T_{p,j}$  are temperatures of two particles in contact;  $R_c$  is the thermal resistance which can be determined based on the Hertz theory by means of the heat conductivity of the considered particles and the Hertz contact radius.

Kuwagi et al. [65] based their work on Rong and Horio [152], who assume that each particle is surrounded by an interstitial gas layer through which the heat conduction takes place. By modifying Rong and Horio's model for the representative particle model (the model is briefly described in Section 3.1.1), they obtained a correlation which describes the contact heat transfer between several particles as follows:

$$\dot{Q}_{pp} = \sum_{n=1}^{NP_a} \left( d_{p,small}^2 k_s \frac{T_{pn} - T_p}{d_{p,small}} \right) + \sum_{n=1}^{NP_b} \{h_{pn} (T_{pn} - T_p)\} \quad (12)$$

where  $NP_a$  is the number of contacting particles in the same waste lump;  $NP_b$  is the number of contacting particles in a different waste lump;  $d_{p,small}$  is the smaller diameter of two contacting particles;  $T_{pn}$  is the temperature of the  $n$ -th particle;  $h_{pn}$  is the heat transfer coefficient between particles.

Regarding radiation, the net radiative heat flux to a particle is the sum of the radiative fluxes from other particles and from the furnace [63]. It is commonly estimated by either surface-to-surface (S2S) models or models that solve the RTEs (e.g., DO model or P-1 model). The first approach is based on the net exchange formulation between surfaces, and the heat radiation from particle  $i$  to particle  $j$  is computed as:

$$\dot{Q}_{ij} = \alpha_j F_{ij} \dot{Q}_i \quad (13)$$

where  $\alpha_j$  is the absorption coefficient of the particle  $j$ ,  $F_{ij}$  is the view factor,  $\dot{Q}_i$  is the radiation energy leaving surface  $i$  [63]. Claiming that using view factors is computationally demanding, Wissing et al. [60] adopted the concept of "radiation control volume" in which a target particle exchanges radiative energy with neighbouring particles [155]. There are two main issues concerning the S2S model. Firstly, it ignores the influence of participating media. Secondly, the method depends strongly on the orientation of the surfaces relative to each other, which is very difficult to quantify

in MSW applications. These two problems can be somewhat resolved by using the second approach. The DO model solves the RTE for a finite number of discrete solid angles, whereas the P-1 model solves a simple diffusion equation for the incident radiation ( $G$ ). Using the P-1 model, Kuwagi et al. [65] computed the radiative heat transfer to a particle as:

$$\dot{Q}_{rad} = -4\varepsilon_{pi} A_{pi} \sigma T_{pi}^4 + \varepsilon_{pi} A_{pi} G \quad (14)$$

### 5.1.4. Heat transfer from the combustion chamber towards the fuel bed surface

Thermal radiation from the freeboard is an important heat transfer mechanism. It is generally computed using the law of Stefan-Boltzmann, assuming that the fuel bed surface is totally enclosed with furnace walls, or is only partly enclosed if the view factor is introduced [60,63,73]. Convection is sometimes considered, making the general form of the equation for supplying heat [25]:

$$\dot{Q}_{surface} = A_f h_c (T_\infty - T_s) + A_f \varepsilon \sigma (T_{wall}^4 - T_s^4) \quad (15)$$

## 5.2. The combustion of volatiles within the waste bed

It is unclear whether gas-phase reactions within the fuel bed play a significant role in its overall thermal degradation. For the sake of simplicity, some models completely neglect homogeneous reactions between the primary air and the pyrolysed products in the waste bed [63]. Most models, however, employ a simplified combustion model in which volatiles are represented as a mixture of light gas components (e.g.,  $CH_4$ ,  $CO$ ,  $CO_2$ ,  $H_2$ , etc.) and a pseudo-heavy hydrocarbon component (i.e., tar). These models compute the reaction rate based not only on the intrinsic kinetic rate but also on the mixing rate. For more details, readers are suggested to read the review by Khodaei et al. [31] since homogeneous reactions are fundamentally similar for biomass and MSW.

## 5.3. Solid mixing on the moving grate

### 5.3.1. Simulating the fuel mixing in the waste bed model

In full-scale grate-firing systems, different stoking mechanisms (e.g., forward-stoking, backward-stoking, tumblers) are used to enhance the bed's burning behaviour. They facilitate the contact between the solid waste and the primary air, promote heat transfer, and improve combustion stability [60,83]. Excessive mixing, on the other hand, can cause ignition delay and quenching of the flame [54,83]. Since the mixing of solid fuel is an important mechanism in moving-grate applications, including it into waste bed models will improve their accuracy.

The phenomenon of particle mixing in a moving bed can be regarded as a combination of three mechanisms. At the smallest scale, the *diffusion mechanism*, which is an analogy to gaseous molecular diffusion, governs the random movement of one particle relative to others. The *convection mechanism* represents the exchange between groups of adjacent particles, caused by the movement of the grate bar. The *shear mechanism* describes the change in the configuration of components by slip planes, which is due to different moving speeds of waste particles on the moving grate bar [83,156].

Prior studies have made an effort to include waste mixing to some extent. The most simple way to tackle this phenomenon is to assume an exchange of certain sections in the waste layer from a cold region to a flame region [54]. On a more advanced level, Beckmann et al. [157] split a grate into different zones, each of which was considered as a continuous stirred reactor. The mixing due to grate movements is modelled by the exchange of species between zones. These two studies are considered to be too simple and do not provide a realistic simulation of the actual mixing process [83].

A third method, which was proposed by Yang et al. [83], assumes that the diffusive mechanism dominates the particle motion and for this reason, introduces the diffusion coefficient  $D_s$ . The distribution of solid components is obtained by solving the solid species equations (Eq. (4)). The effect of fuel mixing on the heat transfer is accounted for using the concept of effective thermal conductivity ( $k_{eff}$ ) as [83]:

$$k_{eff} = k_s + \rho_{sb} C_{ps} D_s \quad (16)$$

The challenge of modelling heat transfer due to the motion of fuel particles in packed bed systems was previously reviewed by Ström et al. [158]. They brought up two additional approaches called “moving coordinate system” [159] and discrete “compaction movement” [90]. Both models adopt the concept of bed compaction (i.e., bed shrinkage) which is caused not only by the movement of the grate but also by the uneven combustion of the solid fuel. Using an empirical shrinkage number and defining the collapse condition of a local cell, they were able to describe somewhat the motion of solid particles within a packed bed.

In a study by Ismail et al. [80], the solid mixing was accounted for partially by considering the disturbance it causes to the gas phase. The dispersion coefficient ( $D_{ig}$ ) of the gas phase was modified as:

$$D_{ig} = \frac{C_{ps} D_s \rho_{sb}}{\phi C_{pg} \rho_g} + 0.5 d_p u_g \quad (17)$$

The most direct way to deal with fuel mixing is to use DPM. However, underlying mechanisms such as aggregation and bed collapses are still too complex to be included in the description of the solid phase [158]. Recently, Wissing et al. [60] used the DPM approach to study the three most common grate designs (forward stoking, backward stoking and tumbler grate) with specific furnace geometries (centre flow, counter flow or co-current flow arrangements). While indicating the potential of this approach, they also pinpointed some limitations regarding the assumption of spherical particles.

### 5.3.2. Stochastic models

The concept of particle diffusion [59,83] assumes that the particle movement follows Fick's law, in analogy with the molecular diffusion of gases:

$$\frac{\partial C_s}{\partial t} = D_s \frac{\partial^2 C_s}{\partial Z^2} \quad (18)$$

where  $C_s$  is the solid concentration,  $Z$  is the distance in the direction of dispersion and  $D_s$  is the diffusion coefficient which can be estimated using stochastic models based on the random walk theory and the Markov process [26,77,156,160].

Essentially, a grate is divided into small cells in which the progression of particles to neighbouring cells is random and can be computed using probability theory. Goh et al. [77] described the movement of particles on the grate as a series of local swaps between particle positions. The “decision” that a local swap takes place is made by comparing the random probability of each cell with a global value. The global value is computed from the standard deviation of the tracer distribution in a grate experiment. Nakamura et al. [26,160] assumed that the transition probabilities of waste particles do not depend on their previous state in time, but are based on the initial profile of MSW feed and a step transient matrix. The step transient matrix is comprised of the probabilities that solid particles remain in the current cell or progress to a neighbouring cell. These transition probabilities depend on feed rate, particle size, bed density, geometry of the grate, and stoking frequency. Li et al. [156] used a similar approach to quantify the mixing of MSW in the vertical direction on the grate.

These stochastic models were successfully applied to study waste bed mixing in small and industrial-scale grate systems but

failed to couple with the waste bed models. In these stochastic models, the applied diffusion coefficients along the bed length and the bed width were 0.03 – 3.6 cm<sup>2</sup>/min and 0.02 – 0.19 cm<sup>2</sup>/min for the small-scale model, and 27 – 109 cm<sup>2</sup>/min and 4.11 – 22.7 cm<sup>2</sup>/min for the industrial-scale model. Inconsistently, the most suitable diffusion coefficients for waste bed models were found to be much lower (1.8 to 6 cm<sup>2</sup>/min for the industrial scale). This discrepancy was due to the scale-up factor and the effect of the feeder hopper in the industrial scale grate-firing systems, as explained by Yang et al. [83].

### 5.4. Shrinkage

The volume shrinkage of a waste bed is observed on both particle and bed level. On the particle level, shrinkage is caused by three factors: loss of solid mass, volume change of the gas phase and structural change of the particle [27]. More details on particle shrinkage can be found elsewhere [27,28]. On the bed level, the shrinkage (or bed compaction) can either be continuous (due to the loss of solid mass and the downward movement of shrunk particles) or non-continuous (the sudden collapse of bed structure as a result of local porosity growth) [159]. Most studies, both for biomass applications (as reviewed in two papers [30,31]) and MSW applications, are restricted to the continuous shrinkage phenomenon.

Goh et al. [53] estimated the volume reduction rate of the bed based on thermochemical equilibrium and chemical reaction kinetics. Shin and Choi [78] computed the shrinking factor based on the ash content and the bed density:

$$\frac{V}{V_0} = \left( \frac{m_b}{m_{b,0}} + f_{ash} \frac{\rho_b}{\rho_{ash}} \right) / \left( 1 + f_{ash} \frac{\rho_b}{\rho_{ash}} \right) \quad (19)$$

where  $V$  is the bed volume;  $f_{ash}$  is the mass fraction of ash.

Ismail et al. [80] calculated the shrinkage degree using empirical shrinking coefficients ( $0 < \alpha < 1$ ) and the conversion degree ( $X$ ) as follows:

$$\frac{V}{V_0} = 1 - \alpha_M (X_{M,0} - X_M) - \alpha_{VM} (X_{VM,0} - X_{VM}) - \alpha_C (X_{C,0} - X_C) \quad (20)$$

Using similar parameters, Gu et al. [25] estimated the shrinkage degree by the following correlation:

$$\frac{V}{V_0} = 1 - X_M (1 - \alpha_M) - X_{VM} (1 - \alpha_{VM}) - X_C (1 - \alpha_C) \quad (21)$$

Unlike the continuous porous medium approach, the DPM method intrinsically considers the volume shrinkage of the fuel bed, thanks to its capability to deal with individual particles. The shrinkage of the particles on their own, however, requires a separate modelling strategy.

### 5.5. From fixed bed to moving bed

Modelling a moving bed, in principle, is similar to modelling a fixed bed because the horizontal gradients of temperature and species concentration in industrial moving grates are relatively small [25]. The DPM approach can fundamentally simulate the motion of solid particles and track them with respect to the Lagrangian frame. For the continuous porous medium approach, there are several simple methods to simulate a moving bed. The cascade model [157] describes a moving bed as a series of connected continuous stirred reactors between which materials are exchanged due to the grate movements. The FLIC model introduces the bed velocity into the governing equations of gas and solid phases. Xia et al. [64] computed the x- and y- direction velocities for the solid phase by using the average grate speed and used

the momentum equation to solve the solid velocity in  $z$ -direction. Bermúdez et al. [89] recently developed the so-called saturation feeding methodology. The fresh fuel is introduced to a group of inlet cells. When these cells are oversaturated, the excess of their solid volume is transferred to the neighbouring cell in the direction of bed movement.

Nevertheless, the most common way to model the bed movement is the walking column method [86] (in other words, the Lagrangian method [81]). The idea of this simple strategy is that an imaginary column (i.e., a bed segment) is taken out of the waste bed and followed along the grate. The condition of the bed segment at time ( $t$ ) since ignition ( $t_0$ ) is similar to that of a bed segment at the horizontal distance ( $x$ ) away from the ignition location ( $x_0$ ) on the moving grate:  $x = x_0 + u_B t$ , where  $u_B$  is the travelling speed of the grate (see Fig. 3) [25,79,87].

### 5.6. Channelling

A packed bed is formed by piling up individual MSW components in a natural way, which essentially creates void spaces for the gas phase. Due to the heterogeneity of MSW, some regions have a higher porosity than others, forming “short-cut” channels that allow a significant amount of gas to travel through. This phenomenon, called channelling, is the leading cause of instability in the combustion of waste beds since it is difficult to control the formation, destruction and movement of the channels [72]. Channelling depends on particle shape and size distribution, waste composition, bed operating parameters and grate design [71].

Even though channelling is a widely accepted phenomenon in industrial furnaces, only a few fuel bed models have incorporated its effect. Yang et al. [71] studied the channel flow inside a packed bed by assuming a local bed porosity distribution with the highest values in the middle of the bed. Similarly, Duffy et al. [161] and Hermansson et al. [159] included channelling in their bed models by applying a normal distribution of porosity by means of a position-dependant function [162].

In addition to these studies, Yang et al. [72] and Nakamura et al. [82] developed two stochastic models, which can be embedded into waste bed models to study the development of channels in packed beds. Considering that the particle size distribution is the most influential factor, Yang et al. [72] adopted the concept of Furnas packing of an arbitrary multi-sized particulate system to derive a relationship between the local porosity and the particle size distribution. This relationship is used in the bed model for the porosity calculation, provided that the distribution of particle sizes is described by a probability density function. Unfortunately, this model was not further developed in later work [55,58]. The second stochastic model was introduced by Nakamura et al. [82]. They used the Monte Carlo method to describe the variation in MSW composition, and the Percolation theory to simulate the channelling and break-up of MSW particles. This model was combined with the FLIC model to simulate the transient phenomena in the waste bed. However, the resulting model was not validated and not further developed.

### 5.7. Validation

Validation is an indispensable step in numerical studies to check whether simulation results agree well with the measurement results. WtE is a complex process which involves many uncertainties in feedstock, set-ups, and measurements. Moreover, because of technical limitations and health and safety risks, it is difficult or even impossible to accurately measure certain parameters such as temperature and chemical composition of the gas and solid phase inside the waste bed. As such, it is hard to obtain a compre-

hensive, reliable set of experimental data which can be used for model validation.

Table 7 summarises the existing numerical studies on MSW combustion which were validated with either experimental or industrial data. Lab-scale data are derived from experiments with fixed bed reactors using woody biomass or simulated MSW. Even though these experiments cannot represent the real MSW incinerator accurately, they were able to provide the best possible set of data, including bed temperature, bed mass loss, reaction front velocity and comprehensive gas-phase information [25,53,55,57,62,73,77,78]. Data obtained from bench-scale and industrial experiments were also addressed in several studies [58,60–62,64,65,72]. However, these data are often limited to temperature and composition of the overbed gas phase or flue gas flow.

In-situ instantaneous measurements in a full-scale plant were performed by the SUWIC research group [68]. They developed a so-called *in-situ* measuring ball instrument which allows measurement of temperature, oxygen concentration and tracking of motion events [72]. Using this in-house developed prototype, they succeeded in studying the channelling effect [72], and the effect of the grate movement and waste feeding cycles on the waste combustion process [163].

## 6. Parametric studies of waste combustion in packed beds

Along a moving grate, a waste bed can be divided into six zones, corresponding to the six phases of the waste combustion process: drying, pyrolysis, ignition, gasification, char burning and ash cooling [32]. Near the feed point, solid waste particles start to heat up and moisture is evaporated. Travelling along the grate, these particles are exposed to higher temperatures and are gradually pyrolysed, releasing volatiles, and converted into char. When the temperature reaches a critical point, the ignition of the released volatiles occurs. Further down the grate, the solid waste particles are gasified, and on the bed surface, the remaining char is burnt in the presence of air. Towards the end of the grate, the remaining ash is cooled and withdrawn through the ash extraction hopper. In the vertical direction, four zones can be similarly defined. The primary air is fed from the bottom of the waste bed, creating the drying zone. The pyrolysis zone is above the drying zone where higher temperatures are achieved thanks to the heat dissipated from the bed surface. Gasification and burning zones are situated above the pyrolysis zone, where the char reacts with oxygen in the primary air [14].

Four parameters, i.e., ignition speed, burning rate, peak temperature and reaction zone thickness, are commonly considered to quantitatively evaluate the performance of a packed bed. The ignition speed and the burning rate yield information on the reaction time, on the overall efficiency of the thermal degradation process and on the operational stability. The peak temperature and the reaction zone thickness help to quantify the burning effectiveness, the air/fuel ratio, and the effect of moisture [31].

Numerical modelling proves to be a superior tool for diagnosis, optimisation and new design of grate-firing systems [32]. Although it is very challenging to accurately model the complex process of MSW incineration in every detail, it is feasible to establish the relationship between fuel properties, operating conditions and the performance of the furnace. Table 8 gives an overview of parametric studies which were conducted using the numerical approach. Results of these studies, which are discussed below, can be used as a tool to explain the observations from experimental studies and industrial operation.



**Table 7**

Validation of numerical studies with experimental data.

Author & Year	Validation data	Equipment type
<b>Lab. experiments</b>		
Shin & Choi (2000) [78]	Bed temperature, O <sub>2</sub> concentration over the bed, flame propagation speed	Fixed batch type reactor
Goh et al. (2000) [77]	In-bed gas temperature, bed mass loss, gas concentration (CO, O <sub>2</sub> , NO <sub>x</sub> , CO <sub>2</sub> ) near the bed surface	Fixed bed reactor
Goh et al. (2001) [53]	Bed temperature, bed height, ignition front, bed mass loss, gas composition (O <sub>2</sub> and CO <sub>2</sub> ) exiting the bed surface	Fixed bed reactor
Yang et al. (2002) [55]	Bed mass loss, in-bed temperature and gas composition (CO, CO <sub>2</sub> , O <sub>2</sub> ) above the grate	Fixed bed reactor
Salvador et al. (2008) [73]	Bed temperature, mass loss	Calorimeter cone
Brosh et al. (2014) [61]	In-bed gas temperature	Test plant PANTHA (packed bed)
Brosh et al. (2014) [61]	Particle temperature, the mass-loss rate	Test plant KLEAA (static bed)
Sun et al. (2015a) [57]	In-bed temperature, gas composition (CO, CO <sub>2</sub> , O <sub>2</sub> , NO, CH <sub>4</sub> ) above the grate	Fixed bed experimental reactor
Sun et al. (2015b) [56]	Bed mass loss, gas composition (CO, CO <sub>2</sub> , O <sub>2</sub> , NO) above the bed	1D bench combustion test rig
Matzing et al. (2018) [62]	In-bed gas temperature; overbed gas composition (CO, CO <sub>2</sub> , C <sub>org</sub> ), bed mass loss rate, reaction front velocity	Fixed bed reactor KLEAA
Gu et al. (2019) [25]	Bed mass loss rate; in-bed O <sub>2</sub> , CO <sub>2</sub> , CO above the grate; gas temperature and velocity at the top surface; in-bed temperature above the grate and the bed height	Packed bed rig
<b>Pilot-scale</b>		
Kuwagi et al. (2016) [65]	Gas temperature and composition at the furnace outlet	Small incinerator, 5.8 kg waste
Matzing et al. (2018) [62]	Gas temperatures, fuel mass flow, gas composition overbed	Pilot-scale grate TAMARA, 6 kg waste
<b>Industrial data</b>		
Yang et al. (2001) [72]	Local bed temperature	UK incineration plant
Ryu et al. (2004) [58]	Temperature and O <sub>2</sub> concentration on the bed surface	Marten-type moving grate – a full-scale MSW incinerator 12 tonnes/hr
Brosh et al. (2014) [61]; Matzing et al. (2018) [62]; Wissing et al., 2017) [60]	Gas composition (O <sub>2</sub> , CO <sub>2</sub> , H <sub>2</sub> O) and gas temperature overbed	MHKW Frankfurt - 57 MW <sub>th</sub> , 23 tonnes/hr
Xia et al. (2020) [64]	Temperature and gas composition (O <sub>2</sub> , CO <sub>2</sub> , H <sub>2</sub> O) overbed	750 t/d MSW (Zhejiang Province, China)

**Table 8**

Parametric studies using the numerical approach.

Authors and year	Operating conditions					Fuel properties				
	Bed height	Feed rate	Prim. air	Fuel mixing	Oper. pressure	Mois. content	Size	LHV	Ash content	Density
Ahmed et al. (1989) [165]		x	x							
Shin & Choi (2000) [78]			x				x	x		
Ryu et al. (2001) [54]			x	x						
Yang et al. (2003) [128]						x				
Yang et al. (2004) [164]			x			x				
Yang et al. (2005 & 2008) [59,83]				x						
Ryu et al. (2007) [166]			x							
Huai et al. (2008) [84]	x		x			x				
Simsek et al. (2012) [167]				x						
Sun et al. (2015a) [57]						x				
Sun et al. (2016b) [96]							x			
Sun et al. (2016a) [137]									x	
Wissing et al. (2017) [60]		x		x			x	x		
Gu et al. (2019) [25]					x		x			
Lai & Law (2019) [81]			x							x
Xia et al. (2020) [64]		x								

## 6.1. Fuel properties

*Moisture content* is known to have a significant impact on many aspects of MSW incineration, including energy recovery potential, completeness of combustion, operational stability and pollution formation [31,32]. A higher moisture content lowers the LHV of MSW and reduces the temperature of the ignition front as well as the furnace temperature. As the moisture content increases, the ignition speed decreases and the drying process can be prolonged, taking up to two-thirds of the whole combustion process [57]. High moisture content also reduces the average burning rate and the devolatilisation rate but intensifies the evaporation rate and char oxidation rate. In this case, the primary airflow has to be increased in order to obtain a high burning rate [84,164]. If the burning rate is low, the fuel bed consumes less oxygen, causing a high  $O_2$  concentration in the flue gas, which is energetically not favourable. On the other hand, it causes the combustion stoichiometry to shift to the fuel-lean side [84,164], helping to lower the formation of CO and  $NO_x$  in the flue gas outlet [57,128,164].

Besides the moisture content, the *ash content* of MSW has an effect on its combustion characteristics. Sun et al. [137] noticed that the total mass loss rate and the moisture evaporation rate increase with increasing ash content, while the ignition propagation speed and burning rate decrease. High ash content material is apparently prone to a higher degree of combustion incompleteness.

The *size of waste particles* largely influences the heat and mass transfer in packed beds, as well as the rate of heterogeneous reactions. Generally, larger particles have a lower surface area per unit mass and thus lowering the cooling effect of the primary air [78]. At the same time, they slow down the heating of the bed surface and lower the radiative heat transfer within the bed; hence they delay the ignition and cause a lower burning rate [96]. As a result, it is generally assumed that due to less complete combustion of larger particles, the carbon content in the ash residue is higher, and the concentration of CO and  $CO_2$  in the flue gas is lower. Gu et al. [25], on the contrary, reported that packing of large particles creates a more uniform temperature profile, leading to a relatively early char burnout. The reason might be that a larger particle size increases the effective conductivity, and hence, the heat is dissipated better inside the fuel bed.

The influence of the *waste bed density* on the combustion process was considered by Lai and Law [81]. It was found that denser solid waste generally requires more time for the combustion process, favours fuel-lean combustion and shows a higher peak temperature. Denser materials also tend to produce a thinner reaction zone and reduce the residence time of the reacting gases; hence, less of the devolatilised gas is burnt in the waste bed.

It should be noted that most studies are based on the assumption of uniform particle sizes, except for Wissing et al. [60]. When taking into account particle size distribution, they found that the burning zone spreads more and that a higher heating value leads to an earlier occurrence of drying, volatile release and char burnout.

## 6.2. Operational conditions

Controlling the *primary air supply* (i.e., air flow rate or air distribution) is a common practice to enhance waste combustion in commercial incinerators [54]. The primary air not only supplies oxygen for the combustion but also facilitates the drying process and the transport of the gas phase within the waste bed [78,81,166]. However, a high primary air flow rate results in substantial convective cooling and may thus cause the extinction of the flame [78,165]. Usually, at relatively low primary air flow rates, an increase in air flow rate can enhance the combustion process and raise the peak temperature via high ignition and burning rates

[164]. For optimisation purposes, several researchers [54,78,84] have studied the effect of the primary air flow rate, in combination with other parameters, on the waste combustion characteristics. Huai et al. [84] and Ryu et al. [54] demonstrated that the combustion could be enhanced by controlling three main parameters: the waste thickness, the airflow and the grate mixing. Shin and Choi [78] found that the optimal air flow rate range is determined by the particle size and the LHV of the waste. According to them, low-quality fuels (i.e., fuels such as MSW with a low LHV), especially with small particles, require more attention to controlling primary air supply.

According to Ahmed et al. [165], the *waste feed rate* is another parameter that can be controlled in combination with the primary air flow rate to adjust the combustion characteristics. They noticed that the length of the drying and burnout zones could be reduced by increasing the waste feed rate and adjusting the air flow distribution. A high waste feed rate typically reduces the residence time of individual particles on the grate [60]. On the other hand, the increased feed rate leads to higher heat input, and hence, more violent combustion [64]. Xia et al. [64] investigated the waste combustion at 60% and 110% of operating waste throughput in an industrial incinerator. They found that at 60% throughput, the peak temperature reduces significantly and its location moves backwards to the earlier on the grate.

The *waste bed thickness* can also influence the combustion of waste in two ways [84]. On the one hand, increasing bed thickness gives rise to a higher amount of combustibles present on the grate, thus increasing the temperature in the furnace. On the other hand, increasing bed thickness decreases the fuel mixing degree, consequently causing the flame position to move backwards. Furthermore, it hinders oxygen supply and reduces the degree of burnout.

As mentioned earlier, the *fuel mixing* is very important in grate-firing applications as it helps to enhance the combustion and decreases the time needed for complete burnout. Yang et al. [59,83] reported that a medium mixing degree is favourable, as in this case, the burning rate is maximal while CO emission is minimal. Increasing the mixing rate from low to medium can remarkably increase the moisture evaporation, devolatilisation and burning rates. It shifts the combustion from fuel-rich to fuel-lean and reduces the carbon content in the ash. In contrast, excessive mixing delays the ignition time and may cause the extinction of the flame. Essentially, the optimal mixing degree strongly depends on the waste particle size and shape and on the grate design (i.e., the motion of reverse acting grates) [60,160,167].

Last but not least, the role of the *operating pressure* was recently studied by Gu et al. [25]. They reported that within a pressure range from 0.5 to 1 atm, a lower operating pressure could delay the burnout of the char.

## 7. Current challenges

Sections 2 to 6 have already discussed major issues and recent achievements in fuel bed modelling with a focus on MSW applications. This discussion highlights several challenges that require more research and development efforts. These challenges exist in three primary domains: dealing with the heterogeneous nature of MSW, developing a more advanced modelling strategy and focusing on specific aspects associated with the performance of a real MSW plant.

### 7.1. Heterogeneity of MSW

The generalisation of the waste composition is problematic in much of the published research. Firstly, it is crude to assume that dry MSW contains only lignocellulosic materials that have similar

thermal degradation behaviours as woody biomass. As pinpointed in Section 2.1, plastics and some other fractions (e.g., low stability organic components, rubber, tyres or non-combustibles) might play a crucial role in the MSW combustion process. Hence, these non-lignocellulosic fractions should also be included in the waste combustion models if their mass fraction is significant. Secondly, the physical and thermal properties of solid waste are poorly specified, although they are vital for the accurate modelling of packed beds. By assuming MSW is uniform in size, shape and composition, a model overlooks many aspects typically present in MSW incineration such as channelling, particle clustering and bed collapse. Undoubtedly, simplifying assumptions cannot be avoided due to the limited computational resources, but an accurate model has to cover the most important phenomena taking place in an MSW combusting grate.

The heterogeneity of MSW imposes another problem associated with combustion chemistry. Even though various experimental studies on the kinetics of MSW pyrolysis have been carried out, there is no consensus on a reaction mechanism which is representative for MSW. The same conclusion can be drawn for kinetic models and thermodynamic data. Moreover, with a need to address current issues in WtE (i.e., pollutant and deposit formation, Cl- and S- induced corrosion, and advanced material recovery), the transformation mechanisms of inorganic elements need to be incorporated in the combustion models [32,87]. Finally, a more detailed drying model which takes into account the pressure variation within the fuel bed is suggested, given that moisture evaporation is of great importance in MSW combustion processes and WtE installations in general [30].

## 7.2. Advanced modelling methodologies

The first challenge in modelling waste beds is to comprise the thermal degradation of each thermally-thick particle [28]. In this respect, the DPM approach shows great capability, but at the same time has its limitations. In order to minimise the computational cost, it is only possible to apply a simplified particle model in which particles are uniform in size and shape. However, as discussed in Section 7.1, this assumption is an oversimplification. Besides the conventional DPM approach, several models have been developed to encounter this challenge such as the representative particle model [65], the Euler-Granular multiphase model [64,80] and the multi-scale models [85,129]. Nevertheless, there is a need for the further fitting of these models to make them representative for industrial-scale MSW combustion.

The second challenge in the modelling of waste beds regards the movement of solid particles. Several studies have tried to include the solid mixing, yet no models appear to simulate an actual MSW moving bed accurately. The most common method, as applied in the FLIC model [83,156], can include particle movement to some extent, as well as can model its influence on the heat transfer. However, the solid diffusion coefficients used in the models are chosen somewhat arbitrary as they are inconsistent with values determined from stochastic models. In addition, the determination of diffusion coefficients may constitute an extra obstacle, since only a few stochastic models were proposed and proven adequate for this purpose. In DPM, the particle motion is inherently taken into account, yet the most intricate and important mechanisms related to aggregation and bed collapse have rarely been addressed. The Euler-Granular multiphase method can describe the solid motion. This method has been popular for fluidised beds, but its suitability for packed bed applications remains to be proven.

Another modelling concern relates to the coupling between the waste bed and the freeboard. As pointed out in Section 3.4, a representative study of both the waste bed and the freeboard needs at least two-way coupling. Although coupling procedures have been

reported in literature, there is still some room for development, more specifically regarding the placement of the interface and the implementation of boundary conditions on two sides (e.g., the non-zero temperature and gas velocity gradients at the bed surface [25]).

In addition to these three major challenges, several studies have pinpointed other modelling aspects that could be improved, such as volume shrinkage of the bed [31], pressure drop within the bed [87], multi-dimensional modelling [71], radiation within the fuel bed [30,31], particle-gas surface contact [158], numerical stability [80] and ash blocking of diffusion [78]. Finally, there is a need for obtaining more detailed operational data in order to validate numerical models better [32]. This requires advanced monitoring, testing and experimentation of MSW grate-firing systems.

## 7.3. Studies of MSW combustion aiming at improving the performance of WtE plants

Modelling waste beds is beneficial not only for an in-depth understanding of the thermal degradation of MSW but also for diagnosis, optimisation and design of industrial furnaces. As mentioned earlier in Section 1.2, there are several aspects which could be further developed in industrial MSW incinerators.

Firstly, due to stringent emission limits for NO<sub>x</sub> (e.g., ELV of 200 mg/m<sup>3</sup> based on Industrial Emission Directive 2010/75/EU [168]), it is crucial, not only for WtE plants but also for biomass grate-firing plants, to come up with cost-effective solutions for reducing NO<sub>x</sub> emissions [17,32]. A reduction of NO<sub>x</sub> formation can be obtained by optimising air-gas mixing, air-staging and grate design. More importantly, the injection of ammonia NH<sub>3</sub> in the hot flue gases in the presence of a catalyst (Selective Catalytic Reduction, SCR) or not (SNCR) has been widely applied in WtE plants to reduce the emissions at the stack. SCR has a higher NO<sub>x</sub> reduction efficiency, but it requires a considerable investment cost and imposes high CO<sub>2</sub>-equivalent emissions due to catalyst production and maintenance [169]. On the other hand, the SNCR system, even though it is less efficient, has the potential to reach the required reduction efficiency if carefully applied [17]. Accurate modelling of MSW packed bed combustion in grate-firing applications can help to establish the combustion parameters that assure minimal NO<sub>x</sub> formation and emission.

Another challenge of WtE incinerators is high-temperature corrosion, which limits the efficiency of electricity production and accounts for a high share in the total operating and maintenance cost. Corrosion is currently primarily tackled by Inconel-type protection materials, along with improving operational stability and applying online cleaning systems [17]. Better know-how of the deposit formation mechanism, as well as of the formation and release of associated key elements such as Cl and S [17], could extend the lifetime of corrosive sensitive parts of the boiler. HCl and SO<sub>x</sub> not only play an important role in corrosion but are also unwanted components in the flue gas for environmental and health reasons. Currently, HCl and SO<sub>x</sub> are removed by injecting neutralising chemicals such as Ca(OH)<sub>2</sub> in dry, semi-dry or wet scrubbers [17,32]. Using data from a large-scale WtE plant, De Greef et al. [170] analysed SO<sub>2</sub> and HCl emission data in relation to combustion control parameters (i.e., primary air flow, pressure drop and waste layer thickness). They revealed a strong dependency between the HCl/SO<sub>2</sub> ratio in the raw combustion gas in the furnace and the characteristics of the waste bed. This kind of observations suggests that a better understanding of kinetics and transport phenomena might be helpful to further increase material efficiency in the HCl and SO<sub>x</sub> removal unit [17].

The operational aspects discussed in the paragraph above show the need for an accurate heat and mass transfer model of the different stages in the MSW incineration process, including chem-

ical kinetics and thermodynamics. Most of the above-mentioned aspects are associated with three primary concerns: the heterogeneity of MSW, NO<sub>x</sub> emissions and deposit formation and corrosion. The first one can be tackled by modelling the channelling and solid mixing in the fuel bed and by incorporating the variation of the MSW's chemical and physical properties. The second and third aspects need sophisticated knowledge on the transfer (i.e., kinetic and transport phenomena) of relevant elements including N, S, Cl, K and heavy metals from the waste to the gas phase. For this purpose, a more advanced fuel bed modelling is needed.

## 8. Conclusions

Our world is confronted with increasing concern about the environmental impact and economic aspects of waste generation and treatment. In this regard, thermal waste treatment technologies in general, and WtE plants in particular, do not lose their importance but rather face a growing challenge. The composition of incoming waste streams might be more diverse due to analogous changes in product composition. Furthermore, the incoming waste might have a lower calorific value due to advanced sorting and recycling schemes. The WtE industry has to deal with this changing waste composition, which makes it the main challenge to obtain a maximal energetic efficiency at minimal plant maintenance cost. To this extent, besides the conventional mechanical and thermal aspects, the chemical and material aspects of the waste combustion process have to be considered. In this light, there is a need for more fundamental research on MSW combustion. In particular, focusing on the thermochemical aspects of the waste would be a promising starting point.

Undoubtedly, better understanding the thermal degradation of MSW begins with a better understanding of the physical and chemical characteristics of MSW as a feedstock. Next, it is essential to develop a model that can embody this complexity of MSW. In this sense, the continuous porous medium approach is simple and can run at a low computational cost. Moreover, it can deal with the heterogeneity of MSW if a reasonable local averaging method is implemented. However, the continuous porous medium approach cannot easily solve the thermally thick behaviour of individual particles, nor simulate the grate mixing straightforwardly. The DPM approach can deal with these aspects, but it is computationally demanding. Furthermore, it has not yet excelled in describing the non-uniformity of MSW particles and some critical mechanisms such as bed collapse. All current modelling approaches need to be further developed to be compatible with, and representative for MSW packed bed combustion in grate-firing applications.

The present paper has covered a broad range of considerations in the modelling of MSW packed beds while staying close to the viewpoint of industrial experts. As a result, the outlined needs for future research and development in the field of waste bed modelling are 1) Including the heterogeneous nature of MSW and covering a wide range of MSW compositions and properties; 2) Developing a more advanced modelling strategy that can handle MSW as a multi-component system at multi-levels (particle and bed level) while minimising the computational cost; 3) Studying the formation and transport of chemical species (e.g., containing N, S, Cl, K and heavy metals) during the combustion processes to find cost-effective solutions for preventing and reducing NO<sub>x</sub> emissions, as well as preventing deposit formation and corrosion in WtE plants.

## Declaration of Competing Interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

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