# Simulation of moving grate waste incinerators using the continuous porous medium approach: a comparison between the conventional fixed bed method and a new feeding method

**Quynh N. Hoang*, Jo Van Caneghem*, Tom Croymans**, Rudi Pittoors**, Maarten Vanierschot*****
nhuquynh.hoang@kuleuven.be
*Department of Materials Engineering, Group T Leuven Campus, KU Leuven, Leuven, Belgium
** Keppel Seghers Belgium NV, Willebroek, Belgium
***Applied Mechanics and Energy Conversion (TME), Group T Leuven Campus, KU Leuven, Leuven, Belgium

## Abstract

This paper presents a two-dimensional CFD-based model for simulating municipal solid waste (MSW) incineration grates. The waste bed is considered as a porous medium, characterized by nine scalars representing solid temperature, solid fraction, and solid composition. This model adopts the mass movement approach to describe the solid phase movement on a moving grate. The bed model is coupled with a freeboard model, which yields results comparable with measurements in an existing MSW incineration plant. The specific objective of this study is to compare the computational cost and accuracy between three moving bed models. The first simulation is a 2D fixed bed model (model 1). Its transient solutions are mapped onto the moving grate's horizontal positions using the bed moving speed (model 1). The second simulation (model 2) computes different moving bed zones, and the third simulation (model 3) computes the whole moving bed. Models 2 and 3 simulate the horizontal grate movement by a so-called new feeding method, which mimics the continuous feeding and withdrawal of solid mass from computational cells that make up the waste bed. Because model 3 allows a simulation of the whole moving bed, the gas flow is accurately obtained. However, this advantage is offset by a high computational time, i.e. 3.5 days, and low stability. Hence, it is only recommended for detailed studies on the gas flow field within a moving packed bed. Simulating separate zones (model 2) helps to reduce the computational time by about 75% but causes a loss of accuracy in predicting the gas flow field at the transition between primary air zones. Additional accuracy loss is introduced when the fixed bed method is adopted (model 1), but the computation time is further reduced to a few hours. Because of the trade-off between computational cost and accuracy and the great uncertainty in industrial practice, model 1 is suggested for simulating industrial grate-firing systems.

Keywords: CFD, Municipal Solid Waste, modelling, grate incinerator, moving bed

## 1. Introduction

Grate-firing is one of the main thermal treatment techniques used to recover energy from biomass [1] and municipal solid waste (MSW) [2]. The released heat from solid fuel combustion can be applied directly as a heat source with an overall gross energy efficiency of up to 80%. If the heat is used for electricity production, an efficiency of approximately 30% is obtained [2]. Grate incinerators are favorable for heterogeneous solid fuels such as MSW because of their reliability and flexibility [3]. The incineration grate is primarily responsible for the transport of waste and ash through the furnace. It helps to distribute the primary air into the waste bed and promotes solid mixing to enhance the burning process [3]. While progressing from the waste feeder to the ash discharge area, solid waste undergoes several thermal processes, including drying, devolatilization (i.e., pyrolysis), char gasification and combustion. Accordingly, the waste bed's physical structure changes, causing complicated behaviors such as breaking, aggregation, and collapse. As a consequence, simulating solid-phase movement on a combustion grate is a great challenge.

A few approaches have been proposed to model the solid-phase movement. Their implementation correlates with the general modelling strategy of the packed bed model (e.g., using the continuous porous medium or the discrete phase modelling (DPM) approach). The continuous porous medium approach assumes that the solid phase is a continuum and can be described by a set of governing equations. In theory, the solid movement can be computed by solving its momentum equations. However, due to the lack of physical models for the stress terms, Yang et al. [4] failed to solve the particle velocity using this concept. Instead, their FLIC model limits the solid movement to the horizontal bed movement and bed shrinkage. The model also accounts for the effect of particle mixing on heat transfer.

Ismail et al. [5] and Xia et al. [6,7] developed waste bed models using the Eulerian-Granular multiphase framework. They simulated the motion of solid particles using the kinetic theory of granular flow (KTGF), which is based on an analogy between particle motion and thermal motion of gas molecules. Even though the KTGF is successfully applied to fluidizing bed applications, its suitability for waste on incineration grates is debatable because the waste bed is compact and the solid movement is intermittent [2].

The DPM approach appears to be more suitable for simulating the solid movement in moving packed beds, such as waste beds on incineration grates [8,9]. The motion of solid particles is solved separately based on forces that apply to them, and their position throughout the domain is tracked with respect to the Lagrangian reference frame. Because this approach is computationally expensive, its application to irregular non-uniform waste particles is still subject to further improvement.

In order to retain the computational robustness and cost at a reasonable level, most existing moving bed models separate the solid-phase movement into horizontal and vertical movements. The former corresponds to the grate movement. The latter is simplified to the downward movement caused by mass loss and particle shrinkage (i.e., bed compaction). This concept allows a moving bed to be greatly simplified as a series of consecutive bed segments. It can be applied differently to several types of models. For example, Beckmann et al. [10] assumed that a moving bed is a network of ideal-mixing continuous reactors. Netzer et al. [11] also adopted the reactor network approach but treated the mixing stochastically and allowed more than one inlet and outlet stream in each reactor.

However, the most popular approach for modelling moving waste beds is the fixed bed method, also regarded as the walking column method [12] or the one-dimensional Lagrangian model [13]. Because the grate travelling speed is relatively low [14], a moving bed model can be reduced to a fixed bed model [13–18]. As illustrated in Figure 1, a moving bed is represented as a translational sequence of fixed bed segments. The transient changes of one segment over a time step $\Delta t$ can be translated into corresponding changes over a distance $\Delta x$ [13]. Thus, the bed's condition at position $x$ away from the feeding point ($x_o$) is at the flow time $t$ where $x = x_o + u_B t$ and $u_B$ is the grate travelling speed. The fixed bed method is capable of simulating solid bed combustion representatively whilst minimizing the computational cost. However, it assumes that the gradients of, e.g. temperature and species concentrations, are negligible in the grate moving direction [18], which still needs to be proven.

The current paper is an extension of previous work by the authors on the modelling of MSW combustion in grate-firing systems using the continuous porous medium approach [19]. The existing 2D CFD-based model has two main novel aspects. Firstly, the relation between the gas flow and the bed packing is treated in detail, including turbulence, flow resistance, and heat and mass transfer. Secondly, the model comprises three sub-models that describe the three important mechanisms of the solid phase movement, i.e., the continuous bed shrinkage, bed collapse, and horizontal grate movement. These sub-models are based on the mass movement approach [20–22]. The horizontal grate movement is algorithmically described as the feeding and withdrawal of solid mass from computational cells that make up the moving waste bed. Therefore, it is also called a new feeding methodology [22].

The existing model can be utilized in two ways: as a whole moving bed model using all three mass-movement sub-models or as a fixed bed model using only the continuous bed shrinkage and bed collapse sub-models. For the fixed bed model, the walking column method is adopted to account for the horizontal movement of the waste on the grate. The whole moving bed model is unquestionably superior in capturing the gas flow distribution in a moving waste bed, yet it is computationally expensive. This paper aims to compare the accuracy and applicability of these moving bed modelling strategies.

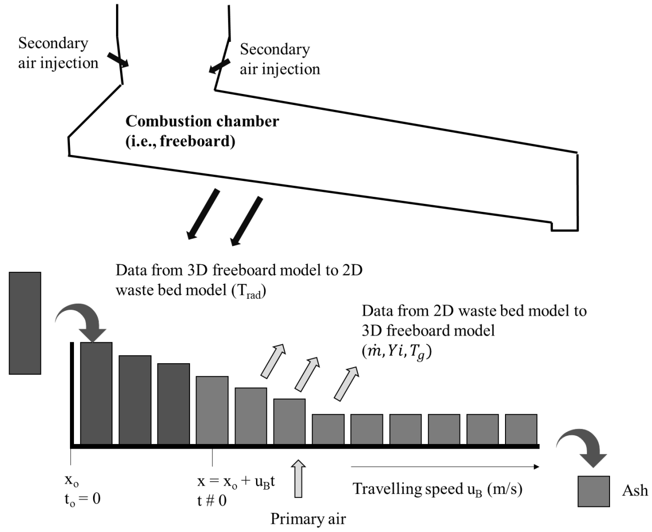


**Figure 1**. Fixed bed (walking column) method and the coupling between the waste bed and freeboard models

## 2. Model description

The packed bed is modelled as a porous medium. The solid phase is treated mathematically as a continuum with a set of conservation equations on a control volume basis (i.e., cell). Unlike the Lagrangian approach, which treats solid particles individually, this method assumes that the waste bed's local properties are volume averages of the surrounding particles. The continuous porous medium approach is less computationally expensive than the Lagrangian approach and hence, is chosen for this study.

The governing equations for both the solid and gas phases are generally formulated in the tensor notation of a scalar, vector, or tensor $\psi$ as [23]:

$$\frac{\partial \psi}{\partial t} + u_i \frac{\partial \psi}{\partial x_i} = D_i \frac{\partial^2 \psi}{\partial x_i \partial x_i} + S(\psi),$$

where the two terms on the left side represent the accumulation rate and the transport by convection, those on the right side are the diffusion term and a source term.

The governing equations for the gas phase consist of the continuity, momentum, species, energy, turbulent kinetic energy and dissipation equations. The effect of the porous bed on the flow field is taken into account by introducing extra momentum source terms (i.e., viscous and inertial loss terms) and turbulent production and dissipation source terms. The momentum source terms are estimated using empirical relations resembling the extended Kozeny-Carman model, which are derived based on two experimental studies on MSW landfills [24,25]. The turbulent source terms are calculated based on Nakayama and Kuwahara [26]. Furthermore, the heat and mass transfer coefficients between the solid and gas phase are estimated using the correlations of Achenbach et al. [27].

The local state of the solid phase is characterized by nine scalar variables, including the solid temperature ($T_s$), the solid/liquid fraction ($\phi$), and the solid and liquid mass per unit cell ($\rho_i$, $i$ = moisture M, cellulose CE, hemicellulose HE, lignin LI, polyethylene PE, liquid tar TARL, and char C). The transport equations of the solid phase scalars and the coupling between the solid and gases are coded using the C programming language. This code, written in the format of user-defined functions (UDFs), is dynamically linked to the ANSYS Fluent 2019 R1 solver.

### 2.1. General assumptions

The waste bed model incorporates the following assumptions:

- There is a non-thermal equilibrium between the gas and solid phases.
- Particles are thermally thin.

- Waste is a mixture of moisture, inert material and four reference species (CE, HE, LI, PE). Its composition is determined by solving a set of four equations. Two equations correspond to the weighted sum of the masses and lower heating values of the reference species. The other two are empirical correlations between lignocellulosic composition, which are estimated so that the carbon and hydrogen elementary composition of the waste mix in the model approximates the measured values of the input waste (i.e., error of 10% wt. maximum) [19].
- The grate moves at a constant speed.

Furthermore, the following sub-models were adopted:
- The drying process is modelled using a combined heat sink and diffusion model.
- For pyrolysis, the five-step mechanism developed by Matzing et al. [14] is employed.
- The char conversion is simulated using the global reaction model in which the char burning rate is expressed as global chemical and bulk diffusion rates.
- The solid movement is modelled using the mass movement approach as described in Section 2.2.

## 2.2. Modelling the solid phase movement

### 2.2.1. The mass movement approach

The solid movement is simulated as an exchange of solid mass between neighboring cells based on the mass movement approach (i.e., bed compaction model). This approach was introduced by Hermansson and Thunman [20] and developed by Gómez et al. [21]. The mass movement approach is capable of simulating not only smooth bed shrinkage but also discontinuous collapses [20]. Recently, Bermúdez et al. [22] introduced a new procedure, called the *saturation feeding method*, to describe the feeding of solid fuel into the furnace and its movement along the grate.

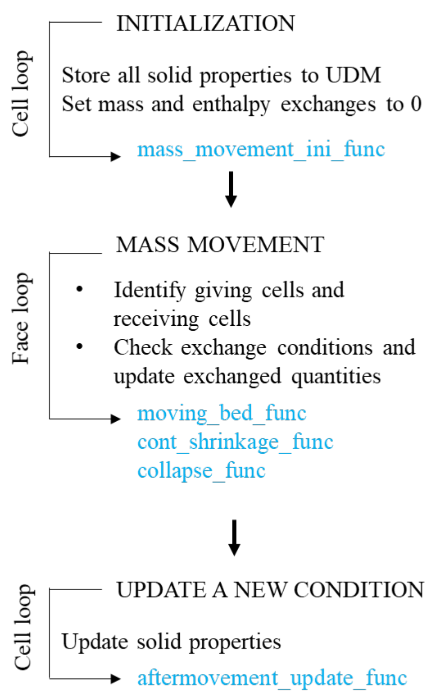


**Figure 2.** The solid mass movement approach

Figure 2 illustrates the complete mathematical routine used in the current work. The initial state of all cells is stored in separate user-defined memories (UDMs). Then, a loop is performed in the whole solid domain to identify the cells that fulfil mass movement criteria. The amount of exchanged mass is calculated based on the current state of neighboring cells and based on which condition is applied to them. Finally, another loop is performed to establish a new condition for these cells (including solid composition, solid fraction, and temperature). Three sub-models based on this approach were developed:

- A continuous shrinkage bed sub-model (*cont_shrinkage_func*) describes the bed compaction due to mass loss, which is computed after the last iteration of every computing time step. The lower cell receives an amount of solid mass from the upper cell proportional to its mass loss due to the decomposition reactions.

- A bed collapse sub-model (*collapse_func*) characterizes the sudden change of the bed structure caused by the local porosity growth and the grate bar's movement. When one of the two following collapse conditions is met, a mass movement is triggered to establish a more sturdy structure. Firstly, if a cell contains less than the threshold minimum solid fraction ($SF_{sat1}$), it is too weak to sustain and hence, will receive mass from the upper cell. Secondly, when a cell, representing a group of so-called solid particles, undergoes a complete decomposition, it turns into a group of ash particles of much smaller size. Under the grate stoking mechanisms, these ash particles can travel down to the bottom of the bed as long as the corresponding receiving cell is not saturated ($SF_{sat2}$). The second process mimics a real mechanism in grate-firing systems where the ash layer formed during the char burning does not pile up on the bed surface but sinks in the waste layer.

- A moving bed sub-model (*moving_bed_func*) illustrates the solid movement in the horizontal direction due to the moving grate. At every time step, an amount of fresh solid fuel is introduced to a group of inlet cells. At the same time, these cells transfer their mass to the neighboring cells in the grate travelling direction. This exchange is cascaded to the end of the bed, where the solid mass is withdrawn. The mass exchange between two cells is determined on the basis of the bed travelling speed and the time step size.

### 2.2.2. Moving bed modelling strategies

The developed packed bed model can be utilized to simulate a fixed bed or a moving bed. Fixed bed modelling requires the continuous shrinking bed and the bed collapse sub-models, whereas moving bed modelling requires all three sub-models. A fixed bed model can be used to simulate a moving bed by adopting the walking column method introduced in Section 1.

This paper compares three strategies of modelling waste combustion on a moving grate (Figure 3):

- Model 1: A fixed bed segment is simulated transiently; its temporal profiles are translated into spatial profiles of a moving bed by using the walking column method
- Model 2: Moving bed zones are computed consecutively. These zones are subject to different primary airflows. The main reason for introducing model 2 is that it is more computationally efficient and stable than the whole moving bed model (i.e., model 3).
- Model 3: A whole moving bed is simulated (i.e., adopting the moving bed sub-model as described in Section 2.2.1).

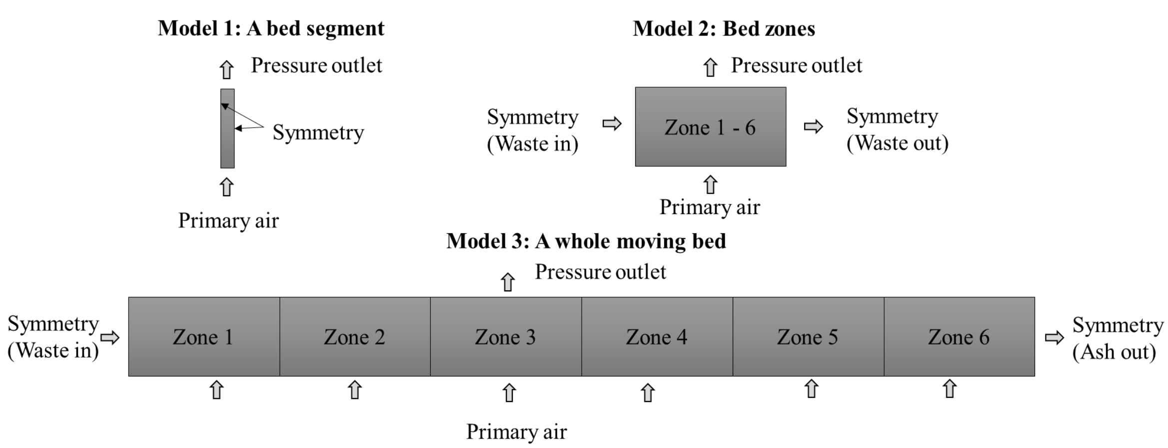


**Figure 3.** Computational domains of the three models that were used to simulate waste combustion on a moving grate

## 2.3. Coupling between the waste bed and the freeboard models

Figure 1 illustrates the two-way interaction between the thermal degradation of waste on the grate and the gas combustion in the above combustion chamber (i.e., the freeboard). A waste model requires the radiation flux from the freeboard as a boundary parameter. The radiation field, however, depends on the gas flow from the waste bed. For this reason, coupling between the waste bed and freeboard models is necessary.

Since it is not this paper's attention to discuss the freeboard simulation, we limit our description to the coupling procedure as follows: 1) The 2D waste segment model is computed transiently at a constant radiation background temperature ($T_{rad}$); 2) Data from the bed surface are averaged and extracted per time step; they contain mass flow rate, mass fractions of gaseous species, and solid/gas temperatures. These temporal data are translated into spatial data, which are interpolated and extrapolated to a 3D profile; 3) Data from the bed model are loaded directly into the 3D freeboard model. In its turn, the steady-state simulation of the freeboard model provides information on the thermal radiation field for the bed model. These three steps are repeated until the $T_{rad}$ profile is converged.

## 2.4. Discretization, initial and boundary conditions

The computational domains (Figure 3) were discretized into quadrilateral cells with grid sizes varying from 2.5 to 10 mm. The finest mesh of 2.5 mm is required where solid waste undergoes the main thermal degradation processes (zones 2 and 3). This grid size was chosen as the result of a grid refinement study; refining cell sizes to 1 mm improved simulation results marginally but increased the computing time significantly.

At the start, the bed domain was considered to be filled with fresh incoming waste and air. Its initial height was estimated based on the waste feed rate and the average residence time. For model 2, the initial conditions of zones 2 - 6 depend on the simulation results of their previous zone. In other words, six zones were computed sequentially, and the initial condition of the next zone was that of the last cells of the previous zone where waste was moving out.

Boundary conditions of the three models are indicated in Figure 3.

## 2.5. Solution procedure

All governing equations for the gas and solid phases were solved simultaneously using a pressure-based finite-volume solver (ANSYS Fluent 2019 R1). For convective and diffusion terms, a second-order upwind discretization scheme was used. The gradients were computed using the least-squares cell-based method. The PRESTO! interpolation scheme was adopted for the pressure term, and pressure-velocity coupling was calculated using the SIMPLE algorithm. For temporal discretization, a first-order implicit scheme was used. Simulations were carried out by two or four Xeon Gold 6140 CPUs @2.3 GHz, 18 cores each. Running at a high number of cores does not always decrease CPU time because parallelization is not beneficial for the mass movement functions. The mass movement approach requires communication between the computer host and nodes at the end of every time step. Therefore, a higher number of cores is only efficient when the number of cells is high enough, which is the case for models 2 and 3.

In general, all models began with a steady-state simulation in which continuity and turbulent equations are enabled. The converged fluid flow was then set as the initial condition for the transient calculation. For model 3, it is challenging to obtain a reasonable initial state of the moving bed. A strict protocol was applied in order to improve the model's stability. First, the whole domain was initialized with the fresh waste composition. Then, a converged steady-state fluid flow was set as the initial condition for a transient simulation solving the solid-phase equations (at a high time step). Once the domain established a time-independent solid profile, a steady-state simulation solving all fluid flow equations was needed. Finally, a transient simulation solving all gas-phase and solid-phase equations was computed for a flow time equal to the average residence time of waste on the grate.

The time step size was chosen to ensure the stability and accuracy of the simulations while minimizing the computational cost. For stability, the Courant number ($Co = u_i \Delta t / \Delta x$, where $u_i$ is the gas velocity) was kept around 1 - 4 at the start of the transient simulation. For accuracy, the time step size was chosen from a sensitivity study with different time-step sizes.

### 2.6. Validation efforts

Because of technical limitations and safety concerns, it is difficult to gain information through measurements inside the industrial furnace, especially within the solid phase [2,20]. Therefore, a comprehensive validation of waste bed models is currently not possible. In common practice, results from the freeboard model, which is coupled with the bed model, are compared with a few measurements in the furnace. Due to the availability of data, we have chosen to simulate an MSW incineration plant in Europe. Information on the plant is given in Table 1 (i.e., MSW incinerator). The waste bed was simulated using the fixed bed approach (see Section 2.2.2) and was coupled with the freeboard CFD model (see Section 2.3). Results of the comparison are given in Section 3.1.

**Table 1**. MSW grate firing systems

| | | MSW incinerator (grate + freeboard) | MHKW Frankfurt incineration grate [9,14] |
|---|---|---|---|
| Thermal load | $MW_{th}$ | 33.2 | 57 |
| Waste feed rate | ton/h | 17.68 | 22.92 |
| Mean residence time | min | 175 | 90 |
| Grate size (length x width) | m x m | 10.3 x 5.7 | 10.36 x 7.3 |
| Furnace height | m | 30 | - |
| Primary air mass flow | kg/h | 47856 (5 zones) | 80825 (6 zones) |
| Primary air temperature | K | 466.7 | 366 |
| Secondary air mass flow | kg/h | 9288 | - |
| Secondary air temperature | K | 306.15 | - |
| Lower heating value | kJ/kg | 6760 | 8640 |
| Moisture | % wt | 42.2 | 29.59 |
| Inert | % wt | 20.1 | 24.66 |

## 3. Results and Discussion

### 3.1. A comparison between simulation results and industrial measurements

Table 2 compares the simulation results with the measurements of the MSW incinerator (Table 1). Measured data were logged on an hourly basis and averaged over 24 hours. A notable variation on these measured data was observed, explained by the inhomogeneity of incoming waste and the uncertainty of on-site measurements. Overall, the model predicts the trend and range of the temperature, as well as the $H_2O$ volume fraction, fairly well. There is a slight overestimation of the overbed gas temperature and an underestimation of the $O_2$ concentration at the outlet. This might indicate that the model somewhat overestimates the combustion rates near the bed surface. Nevertheless, the model is considered to be able to reproduce the major features of a full-scale MSW plant.

**Table 2**. Compare simulation results with measurements on the first pass of the MSW incinerator

| | | Measurements | Simulation results |
|---|---|---|---|
| Temperature above zone 4 | K | 947.4 ± 26.3 | 1020.6 |
| Temperature above zone 5 | K | 819.2 ± 21.7 | 967.8 |
| $H_2O$ @ outlet | vol % | 23.55 ± 1.74 | 22.3 |
| $O_2$ @ outlet | vol % | 5.39 ± 0.08 | 4.3 |
| Temperature @11.54 m furnace height | K | 1314.7 ± 55.6 | 1326.6 |

### 3.2. A comparison of the three moving bed modelling strategies

A sensitivity analysis was performed to compare the three modelling strategies described in Section 2.2.2. In order to limit the computational cost, another grate with lower residence time was chosen for the simulations (i.e., MHKW Frankfurt incineration grate [9,14]). Since the scope of the comparison is the moving waste bed, the freeboard simulation was not carried out. Instead, the radiative boundary condition was taken from the literature. A brief description of the grate is given in Table 1. For full details, readers are referred to the work of Wissing et al. [9] and Matzing et al. [14].

### 3.2.1. Computational effort comparison

Table 3 summarizes the computational requirement for the three considered models. Model 3 requires 83 hours (3.5 days) using 72 computing cores, compared to 22 hours of model 2. Model 1 requires much lower computational cost, i.e., 8 hours using 36 cores. It should also be noted that models 1 and 2 can generally run at much higher stability than model 3.

**Table 3.** Computational requirement

| | | Mesh size (mm) | No. cells | Time step (s) | Flow time (s) | No. computing cores | Computing time (min) |
|---|---|---|---|---|---|---|---|
| Model 1 (fixed_bed) | | 2.5 | 21600 | 0.2 | 5400 | 36 | 460 |
| Model 2 (by_zones) | Zone 1 | 2.5-10 | 67680 | 0.2 | 900 | 36 | 170 |
| | Zone 2 | 2.5 | 249120 | 0.2 | 900 | 72 | 379 |
| | Zone 3 | 2.5 | 249120 | 0.1 | 900 | 72 | 625 |
| | Zone 4 | 2.5-10 | 67680 | 0.2 | 900 | 36 | 120 |
| | Zone 5 | 2.5-10 | 67680 | 1 | 900 | 36 | 15 |
| | Zone 6 | 2.5-10 | 67680 | 1 | 900 | 36 | 15 |
| | Sum | | 768960 | | 5400 | | 1324 |
| Model 3 (moving_bed) | | 2.5-10 | 1351333 | 0.2 | 5400 | 72 | 5000 |

### 3.2.2. Solid-phase

Figure 4 compares the bed height and solid surface temperature calculated by the three models described in Section 2.2.2. The three models show an almost identical trend of the bed height. Solid temperatures are also predicted similarly, except for two specific locations on the grate. The first location corresponds to the char burn-out at x/L=0.55. Although the char burn-out starts at the same location in the three models, model 1 shows a delay in reaching the solid peak temperature of around 1132$^{o}$C. In model 2, the solid temperature peak is observed earlier at a slightly lower temperature, whereas model 3 displays a higher solid temperature peak at 1225$^{o}$C. This inconsistency could be attributed to the gas diffusivity and the local availability of $O_2$ that influence the char burning rate. The second location where the solid temperatures differ is at the end of the grate where ash is cooled off. The cooling of ash is facilitated mainly by the primary air via the convective heat transfer mechanism. Hence, the possible cause of these discrepancies can be attributed to the gas flow field, which is affected by the chosen modelling approach.

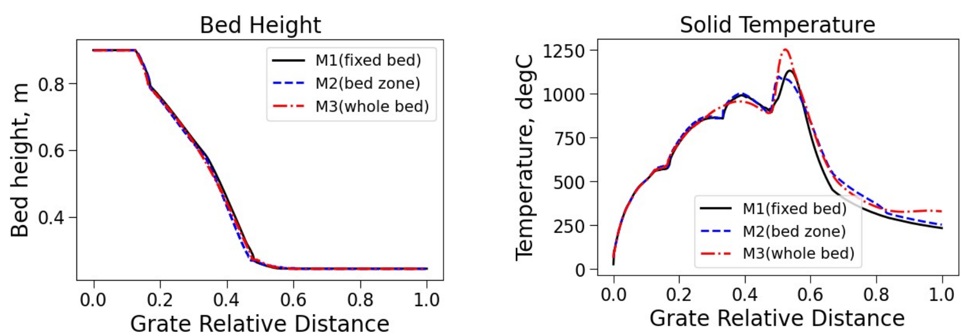


**Figure 4.** Bed height and solid surface temperature calculated by three models: M1 fixed bed segments, M2 consecutive moving bed zones, M3 moving bed as a whole (MHKW Frankfurt incineration grate [9,14])

### 3.2.3. Gas-phase

Figure 5 shows the gas velocity vectors within and above the waste bed as the result of the whole bed modelling (model 3). The figure shows a clear distribution of velocity vectors across six distinct primary air zones. Non-zero horizontal velocity gradients are more obvious in zones 1 – 4 than in zones 5 – 6.

Due to the moving bed modelling strategies, model 1 neglects these gradients completely. In model 2, the gas phase information at the waste-out boundary of the zone on the left is input as boundary conditions at the waste-in boundary of the zone on the right. The following investigates further the impact of gradient orientations on the main characteristics of volatiles leaving the bed surface.

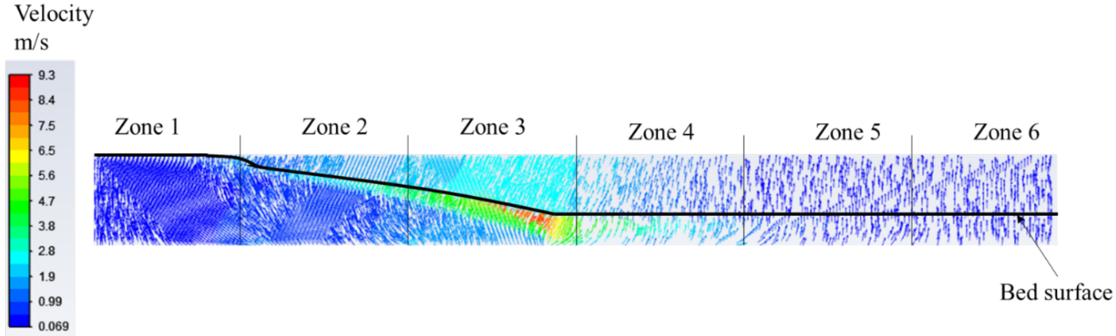


**Figure 5.** Velocity vectors inside and above the moving waste bed, as simulated by the whole moving bed model (model 3, MHKW Frankfurt incineration grate [9,14])

Figure 6 presents the gas temperature at the bed surface calculated by the three models described in Section 2.2.2. The models show similar gas temperature trends. As expected, model 3 illustrates a smooth development of the gas temperature along the grate. Within the first zone (x/L = 0 – 0.17), the gas temperature increases steadily up to 1350°C, suggesting that gas-phase combustion takes place. In comparison to model 3, models 1 and 2 predict a faster increase but at a lower peak in gas temperature. In the next two zones (x/L = 0.17 – 0.5), the temperature remains at approximately 1000°C, very likely because $O_2$ is consumed largely by the char combustion process. After the char burn-out (x/L=0.55), the gas temperature reduces gradually to around 300°C. Models 1 and 2 display a more fluctuated gas temperature profile, especially at the transition between primary air zones. This discrepancy owes to the effect of the horizontal gradients of gas temperature and concentration. Model 1 shows abrupt temperature changes when waste moves from one to another primary air zone. Model 2 shows a smoother profile because the gas phase gradients at the waste-in and waste-out boundaries are coupled in one direction.

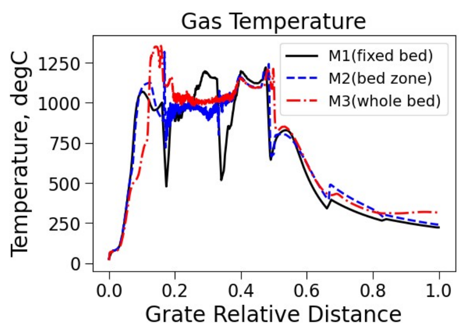


**Figure 6.** The gas temperature at the bed surface, calculated by three models: M1 fixed bed segments, M2 consecutive moving bed zones, M3 moving bed as a whole (MHKW Frankfurt incineration grate [9,14])

As shown in Figure 7, the composition of the gas phase also changes suddenly at the transition between primary air zones, as predicted by models 1 and 2. Similar to the temperature, this fluctuation is more notable in model 1. Compared to model 3, these two models overestimate the release of $H_2O$, CO, and $CO_2$ in zone 1 (x/L = 0 – 0.17). Models 2 and 3 predict comparable results for CO and $CO_2$ concentrations in zones 2 and 3 (x/L = 0.17-0.5). Overall, model 1 performs the worst when predicting the local gas-phase composition.

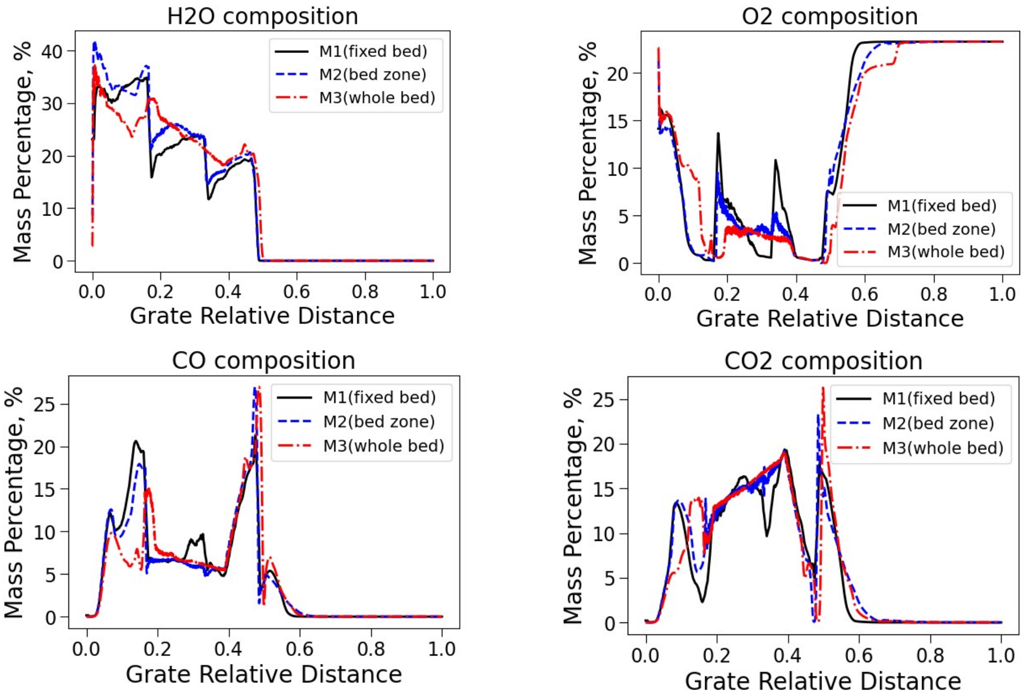


**Figure 7**: Gas composition at the bed surface, calculated by three models: M1 fixed bed segments, M2 consecutive moving bed zones, M3 moving bed as a whole (MHKW Frankfurt incineration grate [9,14])

## 4. Summary

A 2D CFD-based model has been developed to simulate the combustion of MSW in grate-firing systems. The model comprises three mass movement sub-models to simulate the continuous shrinkage, collapse, and horizontal grate movement. The horizontal grate movement sub-model (i.e., moving bed sub-model) allows the full simulation of a moving bed. It is an alternative approach to the fixed bed method (i.e., walking column method), which has been widely used in the literature because of its low computational cost.

Initially, the developed waste bed model (using the fixed bed method) was used to simulate a real MSW incinerator. This bed model, coupled with a freeboard model, yields simulation results comparable to several measurements in the combustion chamber of the waste incinerator. Despite that the model cannot validate the experimental thoroughly due to the complexity of the grate-firing systems, it is able to reproduce the main characteristics of an MSW incinerator.

The main aim of this study is to examine three moving bed modelling strategies: a fixed bed model (model 1), a moving bed model simulating different primary air zones (model 2), and a whole moving bed model (model 3). It is postulated that model 3 presents the most accurate results because it fully incorporates the gas flow distribution. However, the model is less robust and requires a high computational time, i.e. 3.5 days using 72 CPUs. For this reason, this strategy is only recommended for detailed studies on the transport of the gas phase in a moving bed. Model 2 mitigates the computational time to 22 hours using 72 CPUs, and increases the model's stability. However, there is a loss of accuracy in predicting the local gas temperature and composition, as well as the solid temperature during the char burn-out and cooling of the ash. Generally, the computational cost of models 2 and 3 is still high for simulating industrial grate-firing systems. Because of the dynamic interaction between the waste combustion on the grate and the gas combustion in the freeboard, an iterative coupling procedure between the waste bed and freeboard models is required. In other words, a few simulations are needed until convergence is reached, which increases the total computational cost.

Compared to models 2 and 3, the fixed bed model (model 1) requires much less computational time (8 hours using 36 CPUs). However, additional accuracy loss is introduced because model 1 completely neglects the horizontal gradients of gas temperature and concentration inside the moving bed. Nevertheless, the model predicts the bed height and the evolution of the solid temperature similar to model 3. It can also yield satisfactory results on the trend and range of gas temperature and composition. On this basis, model 1 is considered most efficient to simulate grate-firing systems as the system is very complex, involving the heterogeneity of incoming waste streams. Indeed, results from model 1 should always be interpreted with the uncertainty in the estimates of the local gas flow field.

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