

# A one-dimensional model for RDF thermo-chemical conversion on a moving grate of a full scale incineration plant

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## **Abstract:**

Incineration with energy recovery of refuse derived fuel, although being a valuable alternative to waste landfilling, inevitably implies the production of greenhouse gases and the emission of harmful species to human health. The European Directive on construction and operation of incineration plants fixes strict rules on the temperature and residence time of the combustion products within the combustion chambers. Although after-treatment technologies can be used to reduce emissions, it is also necessary to act directly on the combustion process to limit pollutants formation. Developing appropriate simulation models of waste-to-energy plants, therefore, appears extremely important as a way to better control the whole energy conversion.

This work presents a phenomenological model of the thermal conversion of refuse derived fuel into volatiles and residuals (inert char and ash), as occurring on the grate of a real scale waste-to-energy plant. The model is one-dimensional along the grate and reproduces drying, pyrolysis, gasification and combustion of the solid fuel, as it moves invested by the primary air flow and the heat flux due to radiation from the top. The released syngas composition and temperature are determined by a numerical procedure properly accounting for the stiffness of the problem arising during solution. The model results can be used as boundary conditions for the governing equations of the gaseous turbulent reacting flow in the so-called freeboard of the combustion chamber, to fully account for the strict link between the conversion of the solid fuel on the grate and the gaseous combustion of released volatiles.

## **Keywords:**

RDF incineration, Bed model, Grate fired boiler, Waste, Volume averaging theory.

## **1. Introduction**

The global energy demand is rapidly growing and an important part of it is currently met by the use of fossil fuels in combustion systems, which are the main responsible for CO<sub>2</sub> emissions into the atmosphere. In order to reduce the impact of energy conversion on climate change, governments have proposed some ambitious targets, such as, for instance, the so-called "20-20-20" rule set by the European Union. The objective to be reached within the year 2020 consists in the raising of the share of the EU consumption of energy produced from renewable resources up to the 20% [1].

The use of biomasses within combustion technologies is a viable route to achieve the pressing near-term environmental and energy targets, and has been successfully demonstrated in a high number of power plants [2]. Mainly due to the great diversity of biomass resources, efforts are still needed to improve existing systems for achieving more efficient cleaner processes and greater fuel flexibility. For instance, biomasses may differ in size, shape and composition. Waste deriving from human activities is to be considered between them. Waste management, which constitutes one of the main problems of daily life in all the most populated areas of the world, depends on various aspects, such

as the level of technological development, the kind of waste material, the availability of large areas for landfills, and even the cultural level of the local population. Waste combustion, namely incineration, may be used to dispose of a wide range of waste streams including municipal solid waste (MSW), commercial, clinical and certain types of industrial waste. Incineration with energy recovery in waste-to-energy systems couples the need to dispose waste with the requirement of energy from alternative fuels. The formation of pollutants as by-products, however, remains the reason of a widespread concern about the eco-compatibility of this technology, especially as a consequence of a series of local opinion movements still not accepting its use. Incineration is even said to create a sort of landfill in the sky, since it does not destroy waste, but simply changes its form into something which is then almost invisibly distributed around, over hundreds or thousands of square miles [3, 4]. Another critical point is the installation and maintenance costs of large scale incineration plants, which make for different disposal solutions to be often preferred. The controversial feeling about waste incineration reflects into an absolutely in-homogenous spread of this technology over the world, as can be appreciated by looking at Fig. 1, which represents the amount of MSW treated by incineration in various countries, where data are available [5].

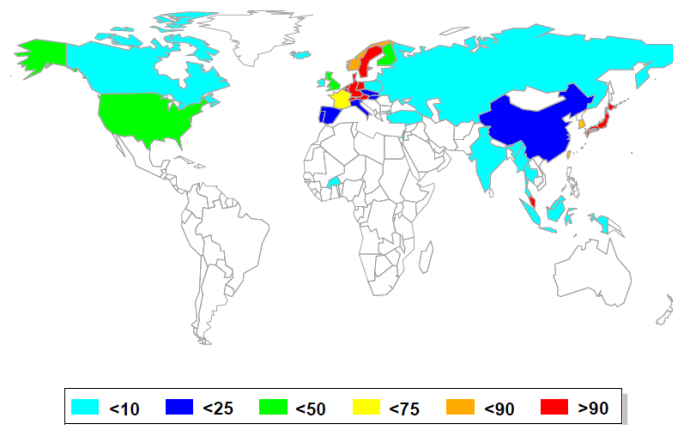


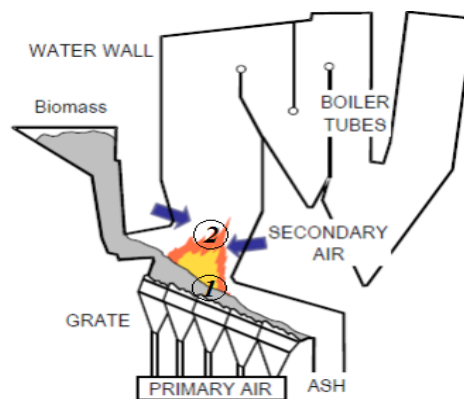
Fig. 1. Incineration of MSW in % [5].

Waste combustion, indeed, may even give rise to more severe pollutant emissions than fossil fuels, as a result of the high content of chlorine, sulphur and heavy metals and the comparatively low ash melting temperature. Policies aimed at restricting the chlorine input for the purpose of reducing dioxin formation in biomass combustion systems have been adopted or recommended by national governments, professional associations and advisory bodies, as well as international treaties.

Nowadays, it is well assessed that the control of the dioxin levels in the exhausts of waste incineration plants can be reached mainly by controlling the thermo-fluid-dynamic processes occurring within the combustion chamber. Therefore, law regulations in many countries enforce stringent operating conditions and set minimum technical requirements for waste-to-energy plants [6]. The European directive 2000/76/EC [7] states that “...incineration plants shall be designed, equipped, built and operated in such a way that the gas resulting from the process is raised, after the last injection of combustion air, in a controlled and homogeneous fashion and even under the most unfavorable conditions, to a temperature of 850 °C, as measured near the inner wall or at another representative point of the combustion chamber as authorized by the competent authority.”

A valuable method to control the temperature and residence time of the combustion products deriving from processing a biomass or waste in an incineration plant is numerical modeling [6]. This may be applicable to different scales of approximation and may eliminate the need to resort to scaling-up of results deriving from lab-scale experiments, which, in this kind of systems, is generally complicated by the strong interaction between turbulence, reaction kinetics, heat release and radiation [8]. The present work focuses on the numerical simulation of the refuse derived fuel (RDF) thermo-chemical conversion occurring in a full scale plant operating in Italy. The combustion chamber has a moving grate furnace with continuous feeding and three vertical channels.

Grate combustion is a well developed technology for burning solid fuels with energy recovery, as well as for thermal treatment of MWS in waste-to-energy systems [9-12]. In moving grate furnaces, a stack of biomass or waste is supplied on a grate and moves lengthwise along it. Subjected to radiative heat transfer from the freeboard and convective heat transfer from the primary air entering from beneath the grate, the solid undergoes a series of conversion processes (i.e. moisture evaporation, devolatilization and pyrolysis, solid char oxidation), that lead to the release of a large amount of volatile combustibles toward the upper part of the boiler. These undergo combustion due to the supply of a secondary air stream. The fuel bed conversion and freeboard combustion are two highly interdependent processes in a grate boiler, which have to be appropriately considered. A scheme of the two zones that can be defined in an incineration plant is given in Fig. 2. The travelling fuel bed is indicated with number 1, while the upper part, namely the freeboard, where gaseous processes take place, is indicated with number 2. For freeboard combustion modeling, 3D (3-dimensional) CFD (computational fluid dynamics) is a valuable tool, with continuity, momentum, energy and species transport equations integrated with appropriate turbulence, radiation, combustion and pollutant formation models [13-17]. The 3D CFD model of the freeboard combustion needs to be coupled with a fuel bed conversion model: the latter provides the velocity, temperature and species mass fraction profiles along the grate length on the of the fuel bed as inlet condition for the freeboard model, while the former provides the incident heat flux to the fuel bed.



*Fig. 2. Scheme of a grate fired boiler of a waste-to-energy plant.*

For bed conversion simulation, very different approaches exist. As an example, the problem of solid fuel bed conversion may be faced with by developing phenomenological models based on the solution of fundamental equations such as the laws of thermodynamics and laws of mass, energy, and momentum conservation and constitutive equations, or by analogy models (empirical or semi-empirical) that mimic the behavior of the fundamental aspects of the considered processes.

In the present work, a phenomenological model is developed for the thermo-chemical conversion of RDF on the grate of a full scale plant. The effect of radiation on the fuel bed top from the surrounding is accounted for in this work, as calculated by a simplified integrated solid-gaseous model, which treats the RDF conversion in a more approximate way [18], namely as based on a two-zone schematization of the bed (drying followed by conversion) [2] and the thermo-chemical equilibrium assumption for conversion. The here presented model for the RDF bed conversion solves balance equations of mass and energy in a one-dimensional description along the grate. Equations are first written at the “phase scale”, then, using a homogenisation technique (volume averaging theory [19]), they are derived for a representative volume. Simultaneously to drying, a pyrolysis mechanism with parallel reaction paths leading to gas, tars and char, is considered [20].

## **2. Characteristics of the incineration plant under study**

The analysis presented in this paper concerns an RDF incineration plant installed in Italy. The thermoelectric power plant is classified as a Plant Powered by Renewable Sources (RES power

plant), pursuant to the *Italian Legislative Decree no. 79 of 16 March 1999 and no. 387 of 29 December 2003*, as well as a co-incineration plant in accordance with the *Italian Legislative Decree no. 133 of 11 May 2005*, implementing the *European Directive 2000/76/EC*, specifically relating to electricity production.

## 2.1 Plant cycle

The plant uses RDF for energy recovery from combustion. The heat generated by this process is exploited to heat water in the closed circuit of the plant, air it is used for Rankine cycle to produce electricity. Attention is here focused on just the solid fuel bed conversion, but some information about the boiler characteristics are given.

### 2.1.1 Steam generator boiler

The plant boiler, with a thermal power of 47 MW<sub>t</sub>, consists of a grate on which the fuel is burnt: the high-temperature gaseous fraction of the combustion products first follows an ascending path in the combustion chamber. This consists of continuous walls of pipes set side-by-side and connected by membranes containing water being converted into steam. The temperature of the combustion products is to be guaranteed to remain above a value of at least 850°C for two seconds, in accordance with current standards. This helps to prevent the formation of products such as dioxins and furans. Subsequently, the combustion products pass through other four vertical heat-exchanging zones in which, by progressively giving up their heat, they allow the steam to be brought to the temperature and pressure levels required for injection into the turbine; the steam, after its expansion in the turbine is discharged into a water-cooled heat exchanger, the condenser, where it returns to the liquid state to be redirected to the boiler in a closed cycle. Solid residues of the combustion consist of the ashes collected on the grate and some lighter-weight residues transported by the combustion gases, together with the unburnt particles collected along the circuit in the boiler until a final filtering stage in a special filter system occurs.

### 2.1.2 Turbo-alternator unit

The turbo-alternator unit consists of a steam turbine-alternator-condenser unit. The triple-spillback, multistage steam turbine converts the energy of the high pressure/temperature steam into mechanical energy; the turbine is coupled with a three-phase power generator, with rotating-diode type excitation including a water-cooling system, by means of a mechanical speed reducer. The 6 kV electricity produced by the alternator is converted to 20 kV and fed into the national distribution network of electrical energy. Part of this energy is absorbed by the plant itself to operate its auxiliary services: pumps, transport and collection systems, air blowers and fume extractors. The available net electric power sent to the grate is equal to 11.5 MW<sub>e</sub>.

## 3. Modelling of the travelling RDF bed

The main characteristics of the RDF and the input data for modeling its thermo-chemical conversion are presented in Tables 1 and 2. These are considered as nominal values, as deriving from a proper measurement campaign realized at the plant, covering a period of one week of normal operation. The primary air volumetric rate is subdivided in four parts, corresponding to the 10, 40, 40, 10% of the total amount over four sequential segments, according to the actual delivery rate.

The RDF travelling bed is here considered as a porous medium composed of three solid phases (organic material (MO), inorganic material (INO) and solid residue of pyrolysis (CHAR)), a liquid water phase (LIQ), and a multi-component gas phase (g). The homogenization method is used, based on the volume averaging theory [19]. This method considers the integration of the conservation equations over a representative elementary volume, indicated as V, containing all the phases, as schematically represented in Fig. 3.

Table 1. Proximate and ultimate analysis of the RDF processed in the plant assumed as nominal.

Proximate analysis	% mass
Organic Matter	69.73
Inorganic Matter	11.07
Char	0
Moisture	19.2
Ultimate analysis	% mass
C	58.84
H	8.21
O	30.71
N	1.99
S	0.25
Cl	0

Table 2. Characteristics of RDF incineration plant and nominal data of main governing variables.

Parameters	Values
Bed length	6.8 m
Width of the bed	7 m
Bed area	47.6 m <sup>2</sup>
Temperature of the incoming RDF	300 K
Mass flow rate of incoming RDF	3.44 kg/s
Primary air temperature	353K
Volumetric flow rate of the primary air	12.19 Nm <sup>3</sup> /s
Lower calorific value of RDF	17025 kJ/kg

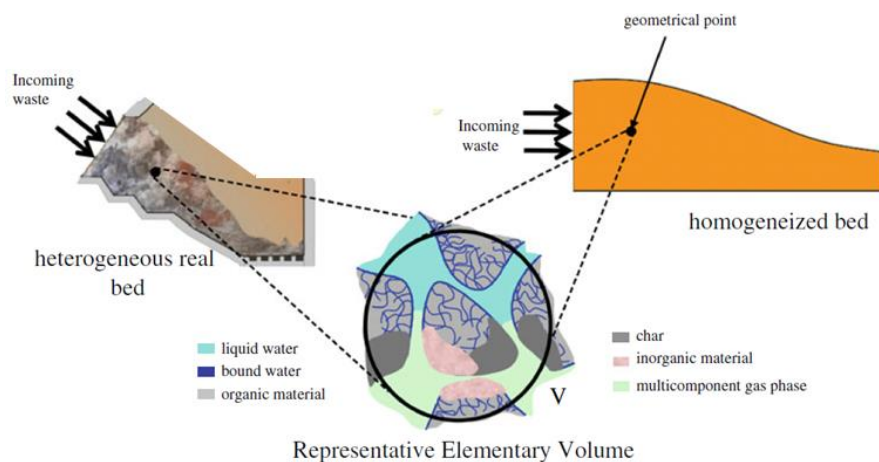


Fig. 3. Principle of homogenization by the method of the volume averaging.

The main assumptions underlying the model are:

- each solid phase is homogeneous and not compressible;
- the compressibility effects of the liquid water are negligible and this phase is homogeneous;
- the gaseous phase is considered as a mixture of  $N$  ideal gases;
- local thermal equilibrium between the solid phases, the gas and the liquid phases is assumed;
- the organic material (which is the only one that decomposes under heating) is treated as wood (several reaction paths and associated kinetics exist in the literature to describe the thermal degradation of wood; here the reaction pathway of reference [20] is used);
- the following chemical species compose the gaseous phase:  $N_2$ ,  $O_2$ ,  $H_2$ ,  $H_2O$ ,  $CH_4$ ,  $CO$ ,  $CO_2$ ,  $H_2S$ ,  $SO_2$ ,  $HCl$ ,  $HCN$ ,  $NH_3$ ,  $NO$ ,  $NO_2$ ,  $C_{10}H_8$ ,  $C_7H_8$ ,  $C_6H_6$ ;

- the calculation of the rate of removal of moisture from the particles  $R_{dry}$  is calculated with a diffusional model according to reference [23];
- chemical kinetics of homogeneous and heterogeneous reactions for the gasification and combustion of char are taken from ref. [20].
- the integration of the balance equations over a cross section of the porous bed and the steady state is assumed to be reached;
- the hypothesis of ideal shrinkage is made: during the gasification process, the lost volume of the bed along the gasifier is only due to gas/solid chemical reaction and liquid evaporation.

Variables and equations of the model are given in Table 3.

Table 3. State variables and equation of the 1D model.

Variables	Equation
	<b>Mass Balance organic matter</b>
$H\varepsilon_{MO}$	$\rho_{MO} U_{bed} \frac{d}{dx}(H\varepsilon_{MO}) = -H r_{pyr}$ (1)
	<b>Mass Balance Char</b>
$H\varepsilon_{CHAR}$	$\rho_{CHAR} U_{bed} \frac{d}{dx}(H\varepsilon_{CHAR}) = -H \sum_i r_{ic}$ (2)
	<b>Mass Balance Inorganic material</b>
$\varepsilon_{INO}$	$\varepsilon_{INO} = \frac{H_0 \varepsilon_{I0}}{H}$ (3)
	<b>Balance of water: Liquid water</b>
$\varepsilon_{LIQ}$	$\rho_{LIQ} U_{bed} \frac{d}{dx}(H\varepsilon_{LIQ}) = -H R_{dry}$ (4)
	<b>Balance species j<sup>th</sup> in the gas phase</b>
$H\bar{\rho}_j$	$U_{bed} \frac{d}{dx}(H\bar{\rho}_j) = H (R_{dry} + \sum_i r_{ij}) + y_j F_{mg0} - \frac{\bar{\rho}_j}{\rho_g} F_{mgH}$ (5)
	where: $R_{dry} \neq 0$ for $j = H_2O$ and $y_j \neq 0$ for $j = N_2, O_2$
	<b>One dimensional energy conservation equation</b>
$H\bar{\rho}h$	$U_{bed} \frac{d}{dx}(H\bar{\rho}h) = \sum_j y_0 F_{mg0} h_0 - \sum_j \frac{\bar{\rho}_j}{\rho_g} F_{mgH} h_j + q_{ray}$ (6)
	<b>Gas phase Total</b>
$H\bar{\rho}_g$	$(H\bar{\rho}_g) = \sum_j (H\bar{\rho}_j)$ (7)
	<b>Total gas flux flowing at the porous medium at H</b>
$F_{mgH}$	$U_{bed} \frac{d}{dx}(H\bar{\rho}_j) = H \sum_i r_{ij} + F_{mg0} - F_{mgH}$ (8)
	<b>Total enthalpy</b>
T	$H\bar{\rho}h = H\bar{\rho}_{MO} h_{MO} + H\bar{\rho}_{INO} h_{INO} + H\bar{\rho}_{CHAR} h_{CHAR} + H\bar{\rho}_{LIQ} h_{LIQ} + \sum_j H\bar{\rho}_j h_j$ (9)
	<b>Ideal shrinkage</b>
H	$H = H_0 \frac{\varepsilon_{g0}}{\varepsilon_g}$ (10)
	<b>Definition of volume fraction</b>
$\varepsilon_g$	$\varepsilon_{MO} + \varepsilon_{CHAR} + \varepsilon_{INO} + \varepsilon_{LIQ} + \varepsilon_g = 1$ (11)

The system is obtained by considering that the phase average of a quantity  $\Psi_\alpha$  in the phase  $\alpha$  over the volume  $V$  containing all the phases, as shown in Fig. 3, is given by:

$$\overline{\Psi_\alpha} = \frac{1}{V} \int_{V_\alpha} \Psi_\alpha dV \quad (12)$$

where  $V_\alpha$  is the volume occupied by the phase  $\alpha$  in the averaging volume  $V$ . The intrinsic phase average is given by:

$$\overline{\Psi_\alpha^\alpha} = \frac{1}{V_\alpha} \int_{V_\alpha} \Psi_\alpha dV. \quad (13)$$

If the volume fraction of the  $\alpha$  phase is defined as:

$$\varepsilon_\alpha = \frac{V_\alpha}{V}, \quad (14)$$

the combination of Eqs. (1) and (2) and (3) leads to the following relationship:

$$\overline{\Psi_\alpha} = \varepsilon_\alpha \overline{\Psi_\alpha^\alpha}. \quad (15)$$

Due to the averaging procedure, the porous medium homogenized in each volume  $V$  represents a geometrical point in the discretization of the bed along its length. The value of any physical quantity at a point in space is given by its average value on the averaging volume ( $V$ ) centered at this point. The system to be solved is composed of ordinary and algebraic equations. Since the ordinary differential equations are of the initial value type, the overall system is solved using Gear's method, which is of the predictor-corrector type. The model is validated on the basis of the results given in ref. [20].

The bed model is here not fully coupled with a simulation of the gaseous phase combustion occurring in the freeboard. In other words, what is here shown as the solution of the formulated problem, relevant to the incineration of the RDF of Table 1, is not the result of a complete computation where the coupling between the bed model and a 3D CFD model of the freeboard is made. This, indeed, would require an iterative procedure until convergence is reached and, obviously a proper tuning of the freeboard combustion model, which is outside the scope of the present work. Nevertheless, the contribution of this work is mainly the detailed description of the various phase changes in the bed to derive the released gas composition and temperature, as a function of the governing parameter of the actual plant and the kind of treated material. The heat flux transferred by radiation from the freeboard toward the bed is accounted for by using the simplified solution of ref. [18]. This allows accounting for variations along the grate, but is just an approximation of the actual one. The effect of the shape of combustion chamber walls on the radiative heat is anyway considered through the P1 model [18]. Specific reaction rates are implemented in the model to account for pollutants formation and transformation in the bed. Other ones must be defined in the model that describes the processes occurring in the freeboard. The full information regarding the reaction rates for pollutants formation is not put in the text for the sake of conciseness. However, it is worth noticing that all the sulfur is released as  $H_2S$  during the pyrolysis step and then  $H_2S$  might be oxidized as  $SO_2$ , and that all the chlorine present in the RDF is released as  $HCl$  and that it is no more transformed in the model. Nitrogen is released as  $HCN$  and  $NH_3$  and might be further transformed into  $N_2$  and  $NO$ .

Further details about the homogeneous and heterogeneous reactions and the associated kinetics are contained in refs. [20 – 23].

## 4. Results and discussion

The results of the overall model are presented for the operating conditions at their nominal values described in the Table 2. Fig. 4 shows the temperature of RDF along the bed, as computed by the model. The solid fuel initially heats-up and loses its moisture in two stages: the first below the boiling temperature where the solid material is slowly heated, and the second in which it reaches

100° C, during which the temperature remains constant until complete evaporation. After this process, the temperature increases rapidly and activates the mechanisms of pyrolysis in the temperature range 300 - 650 °C. Subsequently, after 800°C, gasification and combustion in both the homogeneous and heterogeneous phases occur. This allows the solid fraction of RDF to reach a peak temperature of about 1800 °C. After the peak, the process of oxidation of char with oxygen occurs, followed by the cooling of the system.

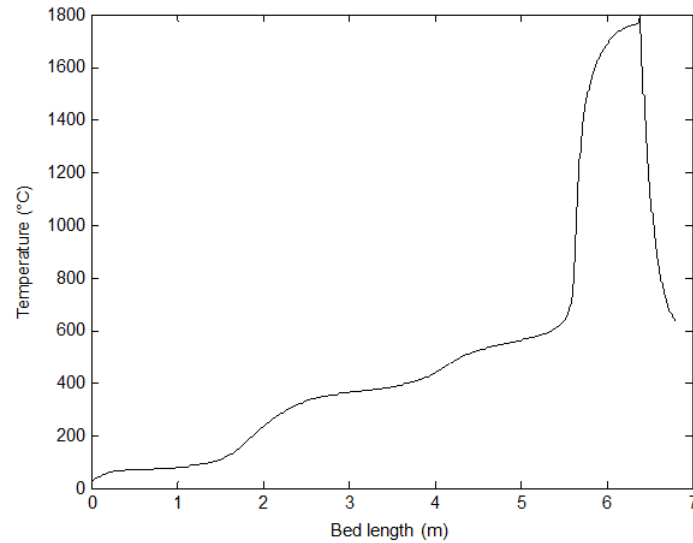


Fig. 4. Temperature of the bed along the grate.

Figs 5 to 7 show the evolution of the average mass fraction of each phase in the bed  $\frac{\bar{\rho}_\alpha}{\sum \alpha \bar{\rho}_\alpha}$ , the intrinsic average mass fraction of some species along the reactor  $\frac{\bar{\rho}_j}{\rho_g}$  for  $j = O_2, CO, CO_2, H_2O$  and the velocity of the gas flowing out of the RDF bed,  $V_g = \frac{F_{mgH}}{\rho_g}$ .

The mass fraction of water decreases and, as a consequence, the mass fraction of the organic matter in the waste bed increases, as shown in Fig. 5. The mass fraction of the water vapor increases in the drying zone (Fig. 6), as well as the velocity of the gas leaving the bed (Fig. 7). Subsequently, the pyrolysis of dry waste occurs. Indeed, the organic material content begins to decrease and simultaneously, the velocity of the gas increases, while its composition is being modified under the production of permanent and condensable gases. The gas leaving the bed is mainly composed of water which is one of the main components of condensable gases. These last are often referred as tars. The pyrolysis step also leads to an increase in the char content of the bed material and inorganic matter. When the organic material present within the bed is fully converted, the pyrolysis process ends. Char consumption starts to occur at the end of the pyrolysis process. This consumption might be associated with combustion reaction and carbon dioxide gasification. Indeed, when the char begins to decrease, all the oxygen decreases to zero because the gasification reaction of char with  $O_2$  takes place, which generates carbon dioxide. The carbon dioxide also goes to zero because of the gasification reaction of char with  $CO_2$ . This is the reason why there is an important amount of carbon monoxide. The velocity of the gas leaving the bed increases due to two effects: the first one is that char solid material is converted into gas, and the second one is the high temperature of the gas.

The presented results show how complex may be the conversion of a solid material as invested by a non uniform air flow from the bottom and a heat flux from the freeboard, even if this last is an approximation of the actual one. The one-dimensional nature of the model allows better differentiating the drying from the conversion zone, if simplified assumptions have to be made based on two- or three-zone schematizations of the occurring phenomena, as is often made [2, 18].



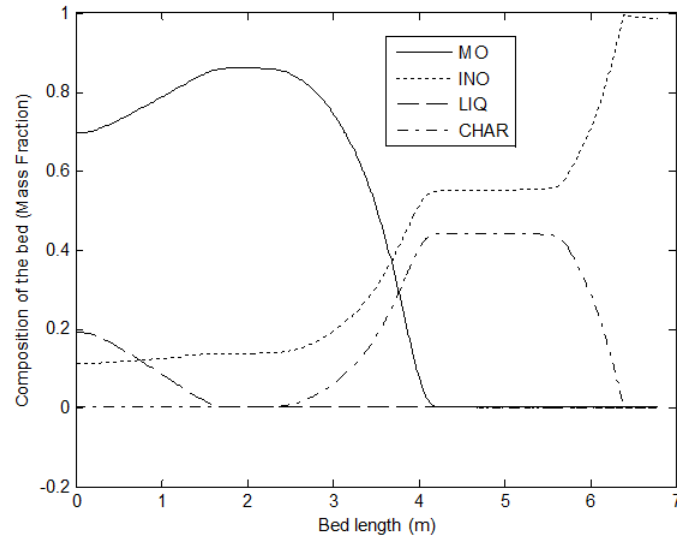


Fig. 5. Average mass fraction of each phase in the bed along the grate.

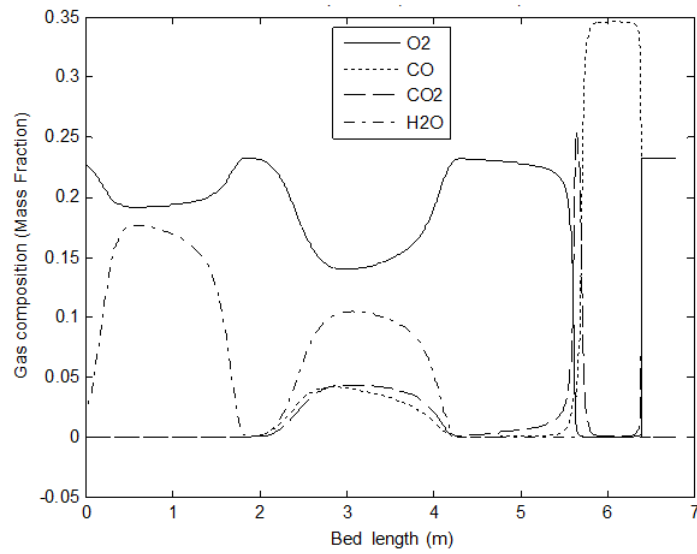


Fig. 6. Intrinsic average mass fraction distribution of species in the gaseous phase along the grate.

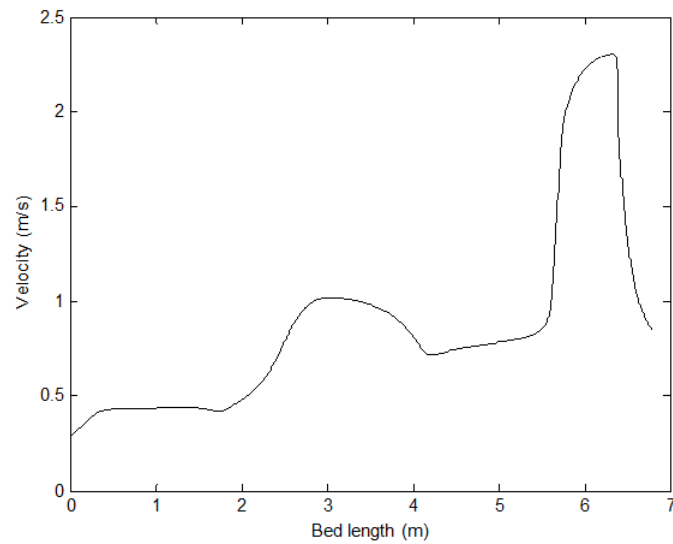


Fig. 7. Average orthogonal velocity of the gas phase along the grate.

## 5. Conclusion

A mathematical model for the thermo-chemical conversion of RDF on the grate of a full scale incineration plant under actual operation is presented. The model is devoted to the description of the physical and chemical phenomena occurring due to the primary air flow investing the fuel bed and the radiative heat flux from the freeboard. This last is estimated according to a previous authors' work using a two-zone model for the bed, but accounting for the freeboard combustion [18]. Although here not coupled with a 3D CFD model of gaseous combustion, the presented numerical approach allows determining in great detail, in a one-dimensional description along the grate, the temperature change due to heating, evaporation, pyrolysis, gasification and combustion, and the various species distribution, in solid, liquid and gaseous phase. The simultaneous occurrence of phase changes and chemical conversion is strictly followed as determined by heating by primary air and freeboard radiation, and then as self-sustained for release of energy. The extension of the actual drying, pyrolysis and combustion zone is highlighted, to which the RDF is subjected while moving along the reactor.

The model is obviously suitable of being coupled with a 3D CFD model of the freeboard to describe the full energy conversion process occurring in an incineration plant. The results obtained as output can be used as boundary conditions for a 3D CFD model of the considered plant that will be properly developed in the near future.

The here described model, indeed, constitutes the first step towards the development of a procedure for the verification of the plant operation with respect to the existing regulations regarding the temperature and residence time of the combustion products in the combustion chamber of a waste-to-energy plant. In fact, it allows deeply characterising the phase change from solid to syngas. Its subsequent coupling with a CFD model of the gaseous phenomena in the freeboard will lead to a detailed description of the internal thermo-fluidynamics. This reveals particularly useful for the evaluation of the temperature of the exhausts two seconds after the last air injection, as requested by the EU specific law and is clearly applicable to any kind of reactor based on grate combustion.

## Nomenclature

$F_{mg0}$	Mass flux air at the bottom of the porous bed ( $\text{kg m}^{-2} \text{s}^{-1}$ )
$F_{mgH}$	Mass flux air at the top of the porous bed ( $\text{kg m}^{-2} \text{s}^{-1}$ )
$H$	Height of the bed or interface between the porous medium and the gaseous environment in the reactor (m)
$H_0$	Height of the bed at the entrance of the furnace (m)
$h_0$	Intrinsic enthalpy of 0 components ( $\text{J kg}^{-1}$ ), for $0 = N_2, O_2$
$h_\beta$	Intrinsic enthalpy of $\beta$ components ( $\text{J kg}^{-1}$ ), for $\beta = MO, CHAR, INO, LIQ$
$h_j$	Intrinsic enthalpy of j components ( $\text{J kg}^{-1}$ ) for $j = N_2, O_2, H_2, H_2O, CH_4, CO, CO_2, H_2S, SO_2, HCl, HCN, NH_3, NO, NO_2, C_{10}H_8, C_7H_8, C_6H_6$
$q_{ray}$	Radiation heat flux ( $\text{W m}^{-1} \text{K}^{-1}$ )
$R_{dry}$	Reaction rate used in the model for the evaporation ( $\text{kg m}^{-3} \text{s}^{-1}$ )
$r_{iC}$	Chemical reaction rate for Carbon in the $i^{\text{th}}$ homogeneous and heterogeneous reactions ( $\text{kg m}^{-3} \text{s}^{-1}$ )
$r_{ij}$	Chemical reaction rate for $j^{\text{th}}$ component in the $i^{\text{th}}$ homogeneous and heterogeneous reactions ( $\text{kg m}^{-3} \text{s}^{-1}$ )
$r_{pyr}$	Chemical reaction rate for pyrolysis ( $\text{kg m}^{-3} \text{s}^{-1}$ )
$T$	Temperature $\alpha$ components (K), for $\alpha = MO, CHAR, INO, LIQ$ , multi component gas phase (g)

$U_{bed}$	Velocity of the bed ( $m\ s^{-1}$ )
$V$	Averaging volume
$V_\alpha$	Volume occupied by the phase $\alpha$ in the averaging volume $V$
$V_g$	Velocity of the gas flowing out at the upper surface of the bed ( $m\ s^{-1}$ )
$y_0$	Mass fraction of 0 component inside input air (-), for 0 = $N_2, O_2$
$y_j$	Mass fraction of nitrogen and oxygen inside input air (-)

### Greek symbols

$\varepsilon_\alpha$	Volume fraction of $\alpha$ components (-), for $\alpha = MO, CHAR, INO, LIQ$ , multi component gas phase ( $g$ )
$\varepsilon_{g0}$	Volume fraction multi component gas phase ( $g$ ) at the entrance of furnace (-)
$\varepsilon_{I0}$	Volume fraction inorganic matter at the entrance of the furnace (-)
$\rho_\beta$	Intrinsic density of $\beta$ components ( $kg\ m^{-3}$ ), for $\beta = MO, CHAR, INO, LIQ$
$\overline{\rho_\beta}$	Intrinsic density average of $\beta$ components ( $kg\ m^{-3}$ ), for $\beta = MO, CHAR, INO, LIQ$
$\overline{\rho_g}$	Intrinsic density average of multi component gas phase ( $g$ ) ( $kg\ m^{-3}$ )
$\overline{\rho h}$	Total enthalpy ( $J\ m^{-3}$ )
$\overline{\rho_j}$	Intrinsic density average of $j^{th}$ components ( $kg\ m^{-3}$ ), for $j = N_2, O_2, H_2, H_2O, CH_4, CO, CO_2, H_2S, SO_2, HCl, HCN, NH_3, NO, NO_2, C_{10}H_8, C_7H_8, C_6H_6$
$\Psi_\alpha$	Physical quantity
$\overline{\Psi_\alpha}$	Phase average of a physical quantity $\Psi_\alpha$ in the phase $\alpha$ over the volume $V$ containing all the phases
$\overline{\Psi_\alpha^\alpha}$	Intrinsic phase average

### Subscripts and superscripts

$\alpha$	Total phases present in the waste: organic matter, char, inorganic matter, water liquid, multi component gas phase
$\beta$	Phases solid and liquid present in the waste: organic matter, char, inorganic matter, water liquid
0	Frontier of porous medium corresponding to the entrance of the furnace
$bed$	Porous medium
$C$	Carbon
$CHAR$	Solid residue of pyrolysis
$dry$	Evaporation
$g$	Multi component gas phase
$i$	$i^{th}$ homogeneous or heterogeneous reactions
$INO$	Inorganic material
$j$	Gaseous species $j$
$LIQ$	Liquid water
$mg0$	Bottom of the porous bed
$mgH$	Top of the porous bed
$MO$	Organic matter
$pyr$	Pyrolysis

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