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A particulate model of solid waste incineration in a fluidized bed combining combustion and heavy metal vaporization

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ABSTRACT

This study aims to develop a particulate model combining solid waste particle combustion and heavy metal vaporization from burning particles during MSW incineration in a fluidized bed. The original approach for this model combines an asymptotic combustion model for the carbonaceous solid combustion and a shrinking core model to describe the heavy metal vaporization. A parametric study is presented. The global metal vaporization process is strongly influenced by temperature. Internal mass transfer controls the metal vaporization rate at low temperatures. At high temperatures, the chemical reactions associated with particle combustion control the metal vaporization rate. A comparison between the simulation results and experimental data obtained with a laboratory-scale fluid bed incinerator and Cd-spiked particles shows that the heavy metal vaporization is correctly predicted by the model. The predictions are better at higher temperatures because of the temperature gradient inside the particle. Future development of the model will take this into account.

1. Introduction

Municipal solid waste (MSW) incineration is becoming more popular throughout the world. This is mostly because it is a convenient means of waste treatment in the context of constant production growth of increasingly urbanized populations. The main advantages include 90% volume and 60% mass reduction, reduced biological reactivity of the waste, and energy production. It benefits from recent European regulations that ban raw wasteland filling, thus imposing sorting and treatment.

Thermal waste treatment suffers from a poor public image, as it generates harmful emissions such as dioxins, furans, and heavy metals (HM). The last are encountered ultimately as residues (bottom ash, fly ash), which are more concentrated than they were initially in the waste, and flue gases. The fate of the metals, that is, their repartition among effluents, depends on their physicochemical history throughout the thermal process. This depends on the metal, its initial speciation and concentration, the type of matrix, and the operating conditions.

It is important to develop tools that simulate incinerators, particularly fluidized bed incinerators, for environmental considerations. It is then essential to better understand the processes that affect HM. The modeling of the local combustion of a waste particle, combined with HM vaporization, will be very useful in improving our understanding of the incineration process so that the various reactions can be controlled.

The combustion of porous and nonporous particles has been widely studied. Many mathematical combustion models have been developed, ranging from models for simple coal particle combustion to models for complex waste particle combustion. This study aims at developing a model that accounts for solid waste particle combustion and heavy metal vaporization from burning particles.

1.1. Coal particle combustion

Coal combustion has been studied extensively, since it occurs in several processes of interest, such as coal, wood, biomass, sludge, and waste combustion [1,2]. Cooper and Hallett [3] modeled coal particle combustion in a fixed bed, which later inspired Menard et al.'s model [4]. This model takes into account the following heterogeneous reactions: coal combustion, CO gaseous oxidation, and mass transfer between the gas and solid phases and within the gaseous phase. Attrition, fragmentation, and agglomeration phenomena are neglected. The reaction scheme is simplified and uses Arthur's law to define the stoichiometry. This bed model provides kinetic information for the local modeling of combustion; it points out the importance of taking into account heat transfer between the solid and gas phases.

Canò et al. [5] studied the combustion of a charcoal particle in a fluidized bed. Their model assumed a moving combustion front and the formation of an ash layer that is subjected to attrition phenomena, which thus reduces with time. The model is based

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Nomenclature

C_M^*	metal equilibrium concentration (mol m^{-3})
C_M^S	metal concentration at particle surface (mol m^{-3})
C_M^g	metal concentration in gas phase (mol m^{-3})
$C_{p,s}$	molar heat capacity of solid (J mol^{-1} K^{-1})
$C_{p,g}$	heat capacity of gas at constant volume (J m^{-3} K^{-1})
D_{Am}	molecular diffusion coefficient for A (m^2 s^{-1})
$D_{eff,A}$	effective molecular diffusion coefficient for A (m^2 s^{-1})
G	gas flow rate (m^{-3} s^{-1})
h_{mA}	mass transfer coefficient for A (m s^{-1})
h_{mM}	metal mass transfer coefficient (m s^{-1})
$h_{s,g}$	gas/solid heat transfer coefficient (W m^{-2} K^{-1})
$h_{sand,g}$	gas/sand heat transfer coefficient (W m^{-2} K^{-1})
K_E	thermodynamic equilibrium constant
L	particle length (m)
N_j	mole quantity of j species (mol)
N_{Ms}	mole quantity of metal (mol)
Q_M	metal flux (mol m^{-2} s^{-1})
r_j	net velocity of j species generation (mol m^{-3} s^{-1})
$\overline{r_{p0}}$	pore mean diameter
R_0	particle radius (m)
R_S	velocity of carbon combustion (mol m^{-2} s^{-1})
S_p	particle external surface (m^2)
S_{ref}	reference surface (m^2)
S_v	surface to volume ratio (m^{-1})
T_F	bed temperature (K)
T_g	gas temperature (K)
T_s	solid temperature (K)
T_{sand}	sand temperature (K)
U_g	gas velocity (m s^{-1})
V_p	particle volume (m^3)
V_{ref}	reference volume (m^3)
y	radial coordinate (m)
y_c	vaporization front coordinate (m)
Greeks	
α_{ij}	stoichiometric coefficient for species j in reaction i
β	molar mass ration carbon/oxygen
γ	stoichiometric coefficient for carbon combustion
δ	asymptotic consumption layer thickness (m)
ΔH_{r_i}	enthalpy of reaction r_i (J mol^{-1})
ε_{mf}	bed porosity
ε_p	particle porosity
ε_{sab}	sand emissivity
θ	volume fraction of particle in the bed
μ	gas viscosity (Pa s)
ξ	particle dimensionless radius
ρ	gas density (kg m^{-3})
ρ_{Ms}	metal concentration in the particle (mol m^{-3})
ρ_s	ratio mole quantity of solid/particle volume (mol m^{-3})
σ	Stefan–Boltzmann constant (W m^{-2} K^{-4})
τ_M	total metal consumption time (s)
τ_p	particle tortuosity

on a quasi-stationary hypothesis with complete combustion (production of CO_2) occurring at the surface of an unreacted core. The reaction is oxygen-diffusion-controlled at the onset, and the majority of the combustion is therefore kinetically controlled.

Porteiro et al. [6] developed a mathematical model that describes the behavior of an isolated particle. The authors state that the formulation is general enough to be valid for any burning particle. On the basis of a cylindrical geometry, their hypothesis permits reduction to a 1D problem, where the independent variable is the radius. Other studies that deal with the combustion of various solids (e.g., [7]) lead to different approaches. For instance, sewage sludge incineration in a fluidized bed is modeled in a spherical geometry. Homogenous particles are modeled by taking into account the evolution of their radius and their density.

Heavy metal release from various burning particles has been studied by thermodynamic or global modeling, that is, without building a local kinetic model [5,7–9]. Moreover, existing models dealing with MSW incineration do not consider the HM vaporization occurring during the particulate combustion, nor do they consider any effects on the combustion from the HM [10–12].

The model developed in this study describes the combustion of a MSW particle, based on a heterogeneous concept of the process, and the quasi-simultaneous volatilization of the HM. The model points out the prevailing processes that govern the coupling between the two phenomena.

1.2. Gas–solid reaction modeling and various concepts of MSW particle combustion

Various models have been created to simulate gas–solid reaction processes with solid consumption (noncatalyzed reactions); most of these models are very complex and require that several parameters be evaluated. The two most common models are the shrinking core (SC) model and the uniform conversion (UC) model. Nonetheless, municipal waste particles have specific physical properties and their combustion cannot be described by either of these two approaches. On one hand, the SC model is unsuitable, since waste particles have a porous structure; on the other hand, the reaction rate is not negligible compared to the diffusion rate. However, the reaction temperature is too high for the UC model to apply.

The so-called asymptotic consumption (AC) model [13] is an intermediate model, which was selected for our approach. This model can be adapted to the solid waste case. It assumes that the chemical reaction occurs in the thin layer located near the particle surface, and simultaneously there is reactive diffusion toward the particle core. The reactive concentration is zero outside of the peripheral layer of thickness δ; when the reactive solid is consumed inside this layer, it is renewed with a new layer of the same thickness. It has been shown that no ash remains around the particle after solid waste combustion; this is integrated into the model. However, the general case allows for the possibility of ash.

1.3. Description of the physicochemical phenomena occurring during waste incineration

During the combustion of a waste particle, whether or not it contains HM, four phases can be distinguished [4]: pyrolysis, pyrolysis gas combustion, residual carbon combustion, and residual carbon gasification.

1.3.1. Pyrolysis

During the pyrolysis process, the organic matter is first weakened. As the temperature increases, it then decomposes into a volatile fraction and a residual solid [14–16]. It is experimentally difficult to quantify the volatile species produced during pyrolysis, as pointed out by all authors.

1.3.2. Pyrolysis gas combustion

The pyrolysis gas mixture contains reaction products, that is, mainly H_2, CH_4, and CO. These species may be oxidized by the oxygen in the air. This is a complex set of reactions (835 steps and 42