HFF 29.2

504

Received 25 April 2018 Revised 24 June 2018 Accepted 3 July 2018

Numerical modeling of municipal waste bed incineration

Adrian Chun Hin Lai

Environmental Process Modelling Centre (EPMC), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University, Singapore, Singapore, and

Adrian Wing-Keung Law

Environmental Process Modelling Centre (EPMC), Nanyang Environment and Water Research Institute (NEWRI), Nanyang Technological University, Singapore and School of Civil and Environmental Engineering, Nanyang Technological University, Singapore, Singapore

Abstract

Purpose – Incineration has become increasingly important in many large cities around the world because of fast urbanization and population growth. The benefits of energy production and large reduction in the waste volume to landfills also contribute to its growing adaptation for solid waste management for these cities. At the same time, the environmental impact of the pollutant gases emitted from the incineration process is a common concern for various stakeholders which must be properly addressed. To minimize the pollutant gase emission levels, as well as maximize the energy efficiency, it is critically important to optimize the combustion performance of an incinerator freeboard which would require the development of reliable approaches based on computational fluid dynamics (CFD) modeling. A critical task in the CFD modeling of an incinerator furnace requires the specification of waste characteristics along the moving grate as boundary conditions, which is not available in standard CFD packages at present. This study aims to address this gap by developing a numerical incinerator waste bed model.

Design/methodology/approach – A one-dimensional Lagrangian model for the incineration waste bed has been developed, which can be coupled to the furnace CFD model. The changes in bed mass due to drying, pyrolysis, devolatilization and char oxidation are all included in the model. The mass and concentration of gases produced in these processes through reactions are also predicted. The one-dimensional unsteady energy equations of solid and gas phases, which account for the furnace radiation, conduction, convection and heat of reactions, are solved by the control volume method.

Findings – The Lagrangian model is validated by comparing its prediction with the experimental data in the literature. The predicted waste bed height reduction, temperature profile and gas concentration are in reasonable agreement with the observations.

Originality/value – The simplicity and efficiency of the model makes it ideally suitable to be used for coupling with the computational furnace model to be developed in future (so as to optimize incinerator designs).

Keyword Numerical modelling

Paper type Research paper



International Journal of Numerical Methods for Heat & Fluid Flow Vol. 29 No. 2, 2019 pp. 504-522 Emerald Publishing Limited 0961-5539 DOI 10.1108/HFF-04-2018/0165 © Adrian Chun Hin Lai and Adrian Wing-Keung Law. Published by Emerald Group Publishing Limited. This article is published under the Creative Commons Attribution (CC BY 4.0) licence. Anyone may reproduce, distribute, translate and create derivative works of this article (for both commercial & non-commercial purposes), subject to full attribution to the original publication and authors. The full terms of this licence may be seen at http://creativecommons.org/licences/by/4.0/ legalcode

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore, and the National Environment Agency, Ministry of the Environment and Water Resources, Singapore, under the Waste-to-Energy Competitive Research Programme (WTE CRP 1601 105).

1. Introduction

Proper management of municipal solid wastes (MSW) has become increasingly important in many large cities throughout the world because of fast urbanization and population growth. An efficient alternative of MSW management is through the adaptation of modern incineration, which has the advantages of high volume reduction (approximately 90 per cent), low space occupation, relatively stable residues, and potential energy recovery. At the same time, to be environmentally responsible, incinerator designers and operators must ensure that the air pollutant emission levels resulting from the incineration meet the strict requirements and regulations of local environmental agencies (Shin *et al.*, 1998).

Globally, a widely used type of incinerator is the moving-grate type (The World Bank, 1999) which the solid wastes are transported along the bottom of the incinerator undergoing various incineration processes. Gaseous products released from the grate rise and enter the freeboard above. These gases then react with each other inside the incinerator under high temperature combustion, and finally the resultant gas mixes are emitted out of the freeboard; with the final solid products being the bottom ashes which are treated and disposed. Optimizing the combustion performance of an incinerator freeboard (Figure 1) can generally minimize the pollutant gas emission levels. Traditionally, this was solely relied on the experience of designs over the past decades, based on intuitions developed from a few established thermo-fluid dynamics principles (Niessen, 2002). With the recent advances in computational power and developments in thermo-fluid dynamics theory, the design of incinerators can now be greatly assisted by using computational fluid dynamics (CFD). CFD enables the prediction of the detailed flow field as well as temperature and gas distribution of the freeboard for a given incinerator setup, so that designs can be performed with better scientific basis. Most importantly, optimization of the incinerator design can now be sought through computation before finalizing with pilot and field testing.

To ensure the CFD predictions are sensible and accurate, it is important to implement the correct boundary conditions in the simulation. A particularly challenging boundary condition is





Waste bed incineration

HFF 29,2 the moving waste bed at the bottom, which undergoes the complex processes of drying, pyrolysis, gasification and char combustion. Its composition and temperature will hence be varied along the grate length which is challenging to simulate. A recent approach developed to predict the waste bed characteristics is the particle-based approach, which the waste bed is represented by a large group of particles that undergoes various heat and mass transfer processes including chemical reactions. For example, Brosch et al. (2014) and Wissing et al. (2017) used the discrete element method to represent the waste bed as reacting computational particles; conduction, convection, radiation, forces between the particles and the gas phase, and various thermochemical processes (drving, pyrolysis, char combustion) are computed for each of the particle so that the changes in the particles mass, composition, and temperature are fully accounted for. The resulting velocity and concentration of the gas released, and the waste bed temperature can then act as boundary conditions for the numerical simulations of the freeboard. The approach has been validated by laboratory experiments and field measurements from a waste incinerator plant, Cordiner et al. (2015) used a simplified approach by pre-defining the particle paths (assuming that the waste bed has a linear reduction in height over the grate length), so that only the particles thermochemical equations need to be solved without the need to consider the particles equation of motion. The resulting gases product concentration and momentum are coupled to the CFD model of the freeboard, by representing them as source terms in the Eulerian momentum and species transport equations. The model predictions were qualitatively compared with available experimental data, and the comparison showed a reasonable agreement in the trend of the waste bed height reduction. In general, particle-based approaches produce finer details of the waste bed, and potentially provide insights to problems that cannot be handled by other simplified models (e.g. effects of waste particle size, non-uniform particle size waste feed); however, the computational time required to complete the simulation is still excessive for engineering applications at present. Thus, the approach is currently used only to consider a limited number of scenarios without the inclusion of the very fine details of the waste bed, or simply as a tool to obtain the boundary conditions for the freeboard.

An alternative approach is to predict the waste bed characteristics by a one-dimensional Lagrangian approach, which the waste bed is represented as a series of non-interfering Lagrangian elements and the changes in its mass, composition, temperature, as well as the resulting gas products are tracked over time. The transient changes of the elements over a time step Δt can then be translated into corresponding changes over a distance $\Delta x = U \Delta t$, where U is the speed of the moving grate. A graphical representation of the approach is given in Figure 2. In



Figure 2. Unsteady onedimensional representation of 2D steady waste bed incineration

this Lagrangian manner, the one-dimensional unsteady or transient problem is translated to the equivalent quasi-steady conditions. There are several representative studies using this approach in the literature. Goh et al. (1998, 2000) developed a mathematical model to account for the bed volume change and various thermochemical processes: the heat and mass transfer within the waste bed were also solved by using the unsteady one-dimensional continuity, momentum and energy equation for both the solid and gas phases. To validate the model, experiments were carried out in a reactor. Samples of simulated waste mixtures were loaded up to about 0.6 m (typical bed height in full scale incinerator) and various thermochemical processes took place inside the reactor over a period of about an hour (the approximate time of travel of waste from the start until the end of the grate). The predicted bed height, temperature, oxygen and carbon dioxide concentration were all in good agreement with the experimental measurements. suggesting this is a sound approach in modeling the steady incineration problem. The group later developed the model to become the fluid dynamic incineration code (FLIC). Shin and Choi (2000) developed another model using similar concepts, with an improved radiation model. Chemical reaction kinetics was also described in more details so that the model can be followed easier. The model was validated by their own experimental measurements in a laboratory reactor. Kaer (2005) developed an equivalent model for straw combustion with hollow cylindrical particles. Milikovic et al. (2013) later extended this type of model to two-dimensional, which is beneficial considering that the waste composition can be spatially non-uniform in practice. However, they did not have suitable experimental data for validation. Other representative studies of model development typically involve further improvement by incorporating effects not accounted for in the original model, for example the effects of devolatilization rate and moisture content (Yang et al., 2003), heat transfer caused by particles mixing from the tumbling action of the grate (Yang et al., 2007), and turbulence effects in the fluid flow by Sun et al. (2015).

The objective of this study is to develop a waste bed model which can predict reasonably the boundary conditions for the freeboard simulation using CFD. As observed by Yin et al. (2008), the final gases composition emitted from the freeboard is likely more sensitive to the overfire jet configuration in the freeboard, rather than the waste bed model used. Thus, for the purpose of examining the performance efficiency and gases emission of the incinerator, it would be sufficient if the waste bed model gives a reasonable prediction of the gas composition and temperature, without needing the fine details of the waste bed. Our model shall be based on the one-dimensional unsteady Lagrangian approach. As discussed above, the adaptation of this approach had been reported in previous studies. However, the chemical reaction kinetics is often not given in details in these studies, and there are also many variations reported in the related literature. In addition, validation in these studies was typically performed by experimental data unique to these studies, without cross-referencing and checking with independent data in the literature to demonstrate the generality of the approach. Thus, so far, a comprehensive and consistent representation of the Langrangian approach is not available for waste bed modeling for CFD freeboard simulations at present. We shall show that the model developed in this study can be a minimal yet fully functional version that can be utilized for CFD simulations to maximize the performance efficiency of the incinerator as well as minimize its pollutant gases emission. The numerical implementation method and the chemical reaction kinetics are first presented in details in the following. The validation of the developed model for reliability and generality and its subsequent applications are then discussed.

2. Numerical modeling of the waste bed

2.1 Problem definition

The problem under consideration is given in Figure 3. The waste bed is considered as an array of waste columns along the y direction, a cross-sectional area A and a height H. The

Waste bed incineration



distribution of the waste columns starts horizontally at x = 0. The setting of both x and y directions allows for more complex spatial variation of waste bed composition in the future. We shall assume that the control columns are identical, such that only one of the columns of mass M needs to be considered. The waste column is dicretized into N control volumes, each of height Δz , such that $H = N \Delta z$. For this study, the individual control volume consists of the solid phase – the waste particles, and the gas phase – the air. The solid phase composition changes from the biomass to various forms of solids and gases over the grate length or time because of drying, pyrolysis, gasification, and char combustion. Thus, the gas phase composition inside the control volume will also vary over time because of the conversion from the solid phase as well as the subsequent chemical reactions among the gases. The

temperature of the control volume which determines the initiation of the thermochemical process and subsequent reaction rates is mainly governed by the radiation from the furnace wall, which propagates along the waste column. The solid temperature T_s along the column will also be changed because of the heat transfer process by conduction, the heat exchange with the gas phase, and the heat of reactions. The temperature of the gas phase T_g along the column will change mainly because of conduction, heat of reactions, and the heat exchange with the solid phase, as well as also the convection from the bottom primary air supply. The details of the governing equations that describe all these processes are given in this section.

2.2 The waste bed mass equation

2.2.1 Drying. We consider one of the identical waste columns which the changes in mass and temperature over time are to be predicted (which experimentally can be considered as a fixed bed reactor). The waste bed mass M can be considered to be composed of the mass of biomass $M_{biomass}$, mass of water (moisture) $M_{moisture}$, and the mass of char M_{char} . Its rate of change over time t can be expressed as:

$$\frac{dM}{dt} = \frac{d}{dt}(M_{\text{moisture}} + M_{\text{biomass}} + M_{\text{char}}).$$
(1)

The change in moisture content can be represented using the Lewis' semi-empirical model (Miljkovic *et al*, 2013) as:

$$\frac{\mathrm{dM}_{\mathrm{moisture}}}{\mathrm{dt}} = -\mathbf{k}_{dry}\mathbf{M}_{\mathrm{moisture}_{o}}\exp\left(-\mathbf{k}_{\mathrm{dry}}t\right), (\Delta H = +40.65\,\mathrm{kJ/mol}) \tag{2}$$

where $M_{\text{moisture}_{\sigma}}$ is the initial moisture content, $k_{dry} = 5.16 \times 10^{-100\beta} \text{ T}[F^{\sigma}]^{48}$ and β is an experimental constant; Miljkovic *et al.* (2013) used $\beta = 1$ in their model, but we found that $\beta = 1.14$ yields a better agreement with the experimental data in the literature and is hence adopted in this study. The energy is assumed to be depleted in the drying process whereby the moisture has been evaporated.

2.2.2 Pyrolysis. The change in the waste biomass after drying over time is assumed to follow the reaction mechanism outlined in Figure 4. The waste first undergoes the pyrolysis reaction; part of it becomes volatiles (devolatilization), and the remaining becomes char. The



Figure 4. Reaction mechanisms used in this study mass fraction indicated as appropriate

Waste bed incineration

reaction rates for devolatilization k_1 and char formation k_2 from the biomass are given in Shin and Choi (2000) as:

$$\frac{dM_{volatile}}{dt} = k_1 M_{biomass} = 5.16 \times 10^6 exp(-10700/T_s) M_{biomass} (\Delta H = -418 \text{ kJ/kg}), \qquad (3)$$

and:

.....

$$\left(\frac{\mathrm{d}M_{\mathrm{char}}}{\mathrm{d}t}\right)_{1} = k_{2}M_{\mathrm{biomass}} = 2.66 \times 10^{10} \mathrm{exp}(-12800/\mathrm{T_{s}})M_{\mathrm{biomass}}(\Delta H = -418 \mathrm{~kJ/kg}).$$
(4)

The rate of change of the biomass is then given as:

$$\frac{\mathrm{d}M_{\mathrm{biomass}}}{\mathrm{d}t} = -(\mathbf{k}_1 + \mathbf{k}_2)\mathbf{M}_{\mathrm{biomass}} \tag{5}$$

where the heat of reaction in equations (3) and (4) are given in Yang et al. (2006).

2.2.3 Char oxidation. The char (C in this context that represents carbon and not concentration) will undergo oxidization to become carbon monoxide and carbon dioxide (Zhou *et al.*, 2005) with the reaction $C + \frac{1}{\theta}O_2 \rightarrow 2\left(1 - \frac{1}{\theta}\right)CO + \left(\frac{2}{\theta} - 1\right)CO_2$. Smoot and Smith (1985) modeled the char oxidation by global modeling, which gave the reaction of a single char particle as $r = v_s M_p k_r \xi_p A_p C_{op}^n$, where C_{op} is the molar concentration of the oxidizer in the gas phase at the surface of the particle, A_p is the external surface area of the char particle equivalent sphere, k_r is the rate constant for the heterogeneous reaction, M_p is the molecular weight of the reactant in the char particle, v_s is the stoichiometric coefficient to identify the number of moles of product gas per mole of oxidant, ξ_p is the particle area factor to account for internal surface burning, and n is the apparent order of the reaction. By using the Newton's law of cooling which accounts for the oxidant diffusion rate (to the char surface), the reaction rate can be expressed as: $r_p = A_p v_s M_p C_{og} \frac{\xi p k_m k_r}{k_m + \xi p k_r}$, where k_m is the mass transfer coefficient. In this study, the model is further simplified such that the reaction rate is expressed in the form of a Arrhenius Equation, described in Zhou *et al.* (2005) and Miljkovic *et al.* (2013), and is given as:

$$\left(\frac{dM_{char}}{dt}\right)_{2} = -M_{char}k_{3}p_{O_{2}} = -8620 \exp\left(-\frac{15900}{T_{s}}\right)M_{char}p_{O_{2}}(\Delta H = -111 \text{ kJ/mol}),$$
(6)

where M_{char} is the mass of the char remaining in the biomass, p_{O2} is the partial pressure of oxygen in the gas. $\theta = \frac{1 + 1/r_c}{1/2 + 1/r_c}$ is the stoichiometric ratio for char combustion, $r_c = \frac{CO}{CO_2} = 12 \exp(-3300/T_s)$ is the ratio of CO-CO₂ formation rate. The heat of reaction can be found in Basu (2010). Together with the char formation rate in Section (2.2.2), the total rate of change of char is then given as.

$$\frac{\mathrm{d}M_{\mathrm{char}}}{\mathrm{d}t} = \left(\frac{\mathrm{d}M_{\mathrm{char}}}{\mathrm{d}t}\right)_1 + \left(\frac{\mathrm{d}M_{\mathrm{char}}}{\mathrm{d}t}\right)_2 \tag{7}$$

The accuracy of this simplified model will eventually be justified by comparison with experimental data in the literature.

510

HFF

29,2

2.3 Homogeneous reactions of gas and tar

Various gases are formed during the drying, pyrolysis, and char combustion processes. The reaction mechanisms that lead to the formation of gases are given in Figure 4. Volatiles are assumed to be composed of various gases and tar, and the percentage mass fractions are assumed to approximately 0.3 and 0.7 respectively (Zhou *et al.*, 2005). The gases mainly consist of carbon dioxide, carbon monoxide, and methane, with the mass fraction 0.65, 0.3, and 0.05 respectively.

The homogeneous reactions and the corresponding heat of reaction among the gases considered in this model are (Zhou *et al.*, 2005; Yang *et al.*, 2006; Basu 2010):

$$CH_4 + \frac{3}{2}O_2 \rightarrow CO + 2H_2O \tag{8}$$

$$\mathrm{CO} + \frac{1}{2}\mathrm{O}_2 \to \mathrm{CO}_2 \tag{9}$$

Following Zhou *et al.* (2005), tar is modeled as hydrocarbons $CH_{1.84}O_{0.96}$, with a molecular weight 95. The corresponding combustion of tar is given as:

$$CH_{1.84}O_{0.96} + 0.48O_2 \rightarrow CO + 0.92H_2O$$
 (10)

The reaction rates of equations (8)-(10) are:

$$\frac{dC_{CH4}}{dt} = k_{CH_4} C_{CH_4}^{0.7} C_{O_2}^{0.8} (\Delta H = -520 \text{ kJ/mol}), \tag{11}$$

$$\frac{\mathrm{d}C_{CO}}{\mathrm{d}t} = k_{\rm CO} C_{\rm CO} C_{\rm O_2}^{0.5} C_{\rm H_2O}^{0.5} \left(\Delta H = -284 \text{ kJ/mol}\right), \tag{12}$$

$$\frac{\mathrm{d}C_{\mathrm{CH}_{1.84}O_{0.96}}}{\mathrm{d}t} = \mathrm{k}_{\mathrm{CH}_{1.84}O_{0.96}} \mathrm{C}_{\mathrm{CH}_{1.84}O_{0.96}}^{0.5} \mathrm{C}_{\mathrm{O}_2}(\Delta H = +42 \text{ kJ/mol}), \tag{13}$$

where the gas concentrations are in mol/m³. The kinetic constants are given as:

$$k_{CH_4} = 1.6 \times 10^{10} \exp\left(-\frac{24157}{T_g}\right),$$
 (14)

$$k_{CO} = 3.25 \times 10^7 \exp\left(-\frac{15098}{T_g}\right),$$
 (15)

$$k_{CH_{1.84}O_{0.96}} = 2.9 \times 10^5 \times T_e \exp\left(-\frac{9650}{T_e}\right),$$
 (16)

where $T_e = \frac{1}{2}(T_s + T_g)$ is the mean temperature which the reaction rate is to be calculated. The heat of reaction can also be found in Basu (2010). Waste bed incineration

HFF 2.4 Waste bed energy and species transport equations

29,2

512

The temperature distribution of both the solid and gas phases within the waste bed column are predicted by solving the energy equations of the two phases. The energy equation for the solid phase is given as:

$$\rho_{\rm s} c_{\rm s} \frac{\partial T_{\rm s}}{\partial t} = \frac{\partial}{\partial z} \left(k_{\rm eff} \frac{\partial T_{\rm s}}{\partial z} \right) + hS(T_{\rm g} - T_{\rm s}) + Q_{\rm moisture} + Q_{\rm pyrolysis} + Q_{\rm char}, \tag{17}$$

where c_s is the heat capacity of the waste bed and is calculated based on the weighted mean c_p of the composing materials, ρ_s is the waste bed density, T_s is the waste bed temperature, T_g is the gas temperature, $h = (Nu \ k_{air}/d)$ is the gas-solid heat transfer coefficient (Nu the Nusselt number, $k_{air} = 0.025$ W/m/K is the thermal conductivity of air, d is the particle diameter), $Q_{moisture}$ and Q_{char} ($Q = \Delta H \ dM/dt$) are the heat sources from drying and char combustion, respectively. The effective thermal conductivity of the solid phase k_{eff} accounts for both the radiative conductivity k_r and the thermal conductivity of the waste bed k_s , such that $k_{eff} = k_r + k_s$. The radiative conductivity is a function of the absorption coefficient κ , scattering coefficient σ_s and bed temperature T_s :

$$\mathbf{k}_{\rm rad} = f(\boldsymbol{\kappa}, \boldsymbol{\sigma}_{\rm s}) \boldsymbol{\sigma} \mathbf{T}_{\rm s}^3,\tag{18}$$

where $\sigma = 5.67 \times 10^{-8} \text{ W/m}^2/\text{K}^4$ is the Stephan-Boltzman constant. For simplification purpose, the function f (κ , σ_s) is approximated as a constant ≈ 4 by comparison with available experimental data of incineration studies (Goh *et al.*, 2000; Shin and Choi, 2000).

The energy equation for the gas phase is given as:

$$\rho_{g}c_{g}\frac{\partial T_{g}}{\partial t} + \rho_{g}c_{g}v_{g}\frac{\partial T_{g}}{\partial z} = \frac{\partial}{\partial z}\left(k_{air}\frac{\partial T_{g}}{\partial z}\right) + hS(T_{s} - T_{g}) + Q_{devolatilization} + \sum Q_{gases},$$
(19)

where c_g is the heat capacity of the gases, ρ_g is the gases, $Q_{devolatilization}$ and Q_{gases} are the heat sources from devolatilization and gas homogeneous reactions respectively, v_g is the gas velocity, taken as equal to the primary air velocity. The thermal conductivity of air is given as $k_{air}=0.025 \ \text{W/m/K}.$

Each gas produced in the processes will mainly be transported by the primary air supply from the bottom of the incinerator, and can be represented by the following species transport equations:

$$\frac{\partial C_{i}}{\partial t} + v_{g} \frac{\partial C_{i}}{\partial z} = \frac{\partial}{\partial z} \left(D_{a} \frac{\partial C_{i}}{\partial z} \right) + r_{i}, \qquad (20)$$

where C_i is the concentration of the individual gas component (there are 6 gases being calculated in this model), $Da = 1.5 \times 10^{-5} + 0.5 v_g D_p$ is the dispersion coefficient of air (Zhou *et al.*, 2005), r_i is the reaction of the individual gas that has been outlined in the previous section.

2.5 Numerical implementation of the model

The finite volume method (Patankar, 1980) is used to dicretize equations (18)-(20), and the solid and gas temperature and the gas concentration are computed as the outputs. The general form of the one-dimensional unsteady convection-conduction discretized equations is:

$$a_{\rm P}\phi_{\rm P} = a_{\rm N}\phi_{\rm N} + a_{\rm S}\phi_{\rm S} + b \tag{21}$$
 Waste bed

where ϕ is the physical quantity to be computed (e.g. temperature, concentration), subscript P is the cell of concern, N and S are the north- and south- side of the cell P respectively (Figure 5); b includes the constant part of the linearized source terms that is expressed as $S = S_c + S_p T_p$. The expression of a_P , a_N , a_S , and b depend on the equation to be solved. For example, for the gas temperature equation, the following expressions can be obtained:

$$a_{\rm N} = \frac{k_{\rm n}A}{\delta z} + \max(0, -\rho v_{\rm g}); a_{\rm S} = \frac{k_{\rm n}A}{\delta z} + \max(\rho v_{\rm g}, 0); b = S_{\rm c}(A \ \Delta z) + a_{\rm P}^0 T_{\rm P}^0$$
(22)

$$a_{\rm P} = a_{\rm N} + a_{\rm S} + a_{\rm P}^0 - S_{\rm P}(A\Delta z); a_{\rm P}^0 = \frac{\rho c_{\rm g} A\Delta z}{\Delta t}$$
(23)

where Sc is the constant source terms (for example the heat sources from reactions), Sp is a coefficient that arises from linearizing the source term (for example the term that comes from the heat exchange between solid and gas phase); A is the cross-sectional area of the reactor, and superscript 0 represents the value of the previous time step. The convection term has been discretized using the upwind scheme. Equation (21) is written for every cell of the waste column, so that a matrix with ϕ as solution can be expressed as:



Figure 5. Definitions of the control volume length and inter-node distances

513

incineration

HFF 29,2

514

Boundary conditions (ϕ_b is the value of the boundary nodes at one end) can be implemented by setting $a_{P1} = 1$, $a_{N1} = 0$, and $b_1 = \phi_b$ such that $\phi_1 = \phi_b$. The boundary value at the other end can similarly be implemented by setting $a_{Pm} = 1$, $a_{Sm} = 0$. If the boundary value is not given but instead the heat flux is specified, an extra equation for their relationship is constructed to determine the boundary value which will then be fit into the matrix in equation (24). The details of constructing the extra equation can be found in Patankar (1980).

The boundary conditions in this model are implemented as such: for the gas phase, the primary air temperature and velocity are specified at the waste bed bottom boundary. At the bed top boundary, the temperature gradient is set as zero and the air velocity is assumed to be constant throughout the waste bed. For the solid phase, the bottom temperature is set to be equal to that of the primary air temperature because of intensive heat transfer between the solid and gas phasees (Zhou *et al.*, 2005). At the top of the solid phase, the boundary temperature is determined by the external convective and radiative heat flux (Park *et al.*, 2010) as follow:

$$\frac{\partial \mathbf{T}}{\partial z} = h(\mathbf{T}_{g} - \mathbf{T}_{s}) + \sigma \mathbf{e}_{s} \left(\mathbf{T}_{f}^{4} - \mathbf{T}_{s}\right)^{4}$$
(25)

where *h* is the heat transfer coefficient (W/m²K), $e_s =$ surface emissivity ranging from 0.7 to 0.9 (0.85 is adopted in this study), T_f is the temperature of the furnace of the incinerator. For the gas species, the gas concentration at the waste bed bottom is set to be the same as that of air. With respect to the initial conditions, both the gas and solid temperatures are set to be the same as that of room temperature (T = 300 K). The gas species concentration is also set to be identical to that of air.

In our simulations, the waste bed, typically of height 0.6 m, is discretized into 20 control volumes, the time step used is 0.02 s. A total time of 3,600 s is being simulated, which is the typical duration for the incineration process to be completed. The matrix in equation (24) is solved by the tridiagonal matrix algorithm for every time step.

3. Model validation

The developed model is to be validated with available literature data. Two representative studies, of on incineration biomass experiments are selected. The waste biomass composition differs significantly among the previous studies, which resulted in the very different behavior reported in the literature.

3.1 Incineration of low-density waste biomass

Goh *et al.* (2000) studied the incineration process by carrying out experiments in a cylindrical combustion chamber. The height of the chamber was 1.5 m and the internal diameter was 0.2 m. The simulated wastes consisted of a mixture of wood, cardboard, paper and vegetables. They were piled up to 0.6 m in the combustion chamber. Primary air was supplied from below the waste bed at a rate of 40 L/min. The furnace temperature, according to the experimental results, can reach up to 1200 K, and it was assumed to be the furnace temperature in this study. Using the measured density and volume fraction of the mixture components, the density of the mixture was calculated to be 190 kg/m³. The gas and solid phase were initially at room temperature, and then the reactor was brought up to the waste bed temperature which started off the various reactions. The temperature at different heights of the waste bed was then measured. Gases were also produced in the process, and the gases concentrations were monitored.

Using the above conditions as input, the model developed in this study can predict the waste bed height, gas concentration, and temperature changes over time. Figure 6 shows the comparison between the predicted and observed heights of the waste bed. The predicted height is approximated by the $M_{bed_o} \times H$, where M_{bedo} is the initial bed mass. It can be seen the prediction is reasonable, except towards the end of the reaction where the predicted bed height no longer reduces which could be because of the fact that the reaction for char oxidation (and hence the reduction in bed mass) is not universal and does not fit perfectly in this case.

The predicted and observed waste bed temperature at different bed height w is shown in Figure 7. Close to the surface (z = 0.52 m), the predicted temperature rises slowly since the energy has been used to heat and evaporate the moisture in the waste bed. Although the slow rise was not noted in Goh *et al.* (2000) experiments, it was commonly observed in others such as Shin and Choi (2000). Afterwards the temperature quickly rises to the furnace temperature because of radiative heat flux; the time for the temperature to rise to the furnace temperature is generally well predicted. For the other bed heights, the model in general gives good predictions to the temperature changes with time. The agreement suggests that the radiative heat transfer (which the temperature heavily depends on) has been simulated correctly.

The gases concentration changes over time are also predicted and compared to the experimental observation in Figures 8 and 9. Figure 8 shows the changes in concentration of oxygen over time, which can be seen to be heavily depleted because of the various oxidation reactions in the incineration processes. A large percentage of the oxygen is used in the oxidation of carbon and carbon monoxide to complete the combustion, which produces carbon dioxide in the process evidenced in the prediction and observation of carbon dioxide concentration over time shown in Figure 9. Note that in the observation, no reaction took place in the first 20 min. This delay in reaction was not seen in other studies (Shin and Choi, 2000), and good explanation was not provided. However, the temperature was also recorded to rise quickly within 5 min after the reactions were initiated. Therefore, in the comparison, the time zero represents the instance which the reactions begin.



Figure 6. Predicted and observed waste bed height of Goh *et al.*'s (2000) experiments

Waste bed incineration



3.2 Incineration of high-density waste biomass

Shin and Choi (2000) studied the incineration process using simulated wastes consisted of moisture and wood (which were converted to ashes after reactions). With the given composition and assuming the density of wood to be approximately 800 kg/m^3 , the density of the simulated wastes is estimated to be 850 kg/m^3 , which is somewhat denser than that used in Goh *et al.* (2000)'s experiments. It is of interest to see whether there is significant difference in behavior when the waste biomass density varies. The generality of the model can also be ensured by comparing the model predictions with measurements in this independent study.

In Shin and Choi's (2000) experiments, the bed of biomass was 0.15 m in diameter, with height 0.45 m. The temperature of the reactor was first brought up to 1,123 K, and then the



wastes were inserted into the reactor. Primary air was supplied at room temperature (assumed 300 K) from below the reactor with a rate of 10-850 L/min. No changes were made to the reaction mechanism in the model. Both the bed height and gas concentration were measured in the experiments over time.

Case No. 7 was chosen as the representative experiment to be presented in Shin and Choi's (2000) study, and the same case is used for comparison with our model predictions. The primary air supply is computed to have a speed of 0.12 m/s. Figure 10 shows the comparison between the predicted and observed waste bed height. The agreement can be seen to be reasonable, especially the slope of the bed height reduction. Comparing this experiment with that of Goh *et al.*'s (2000), it can be seen that the bed height was reducing at a slower speed, probably because of the longer time required for the denser mass to be combusted. The predicted and observed oxygen concentrations are shown in Figure 11.



Figure 10. Predicted and observed waste bed height of Shin and Choi's (2000) experiments



Both showed that the oxygen is consumed heavily during the incineration process but is gradually 'replenished' by the primary air when the incineration process comes to an end. Interestingly, the delay in reaction seen in Goh *et al.* (2000) was not observed in Shin and Choi's experiments. This suggests that the reactions can be sensitive to the differences in the experimental setup and the procedures in running the experiments.

4. Discussion

In the present study, a one-dimensional Lagrangian model has been developed for the modeling of the waste bed which acts as the boundary condition for the CFD simulations of the freeboard. The relative simple model has been shown above to give predictions that agree reasonably well with the laboratory scale experimental data from Goh *et al.* (2000) and Shin and Choi (2000). Although the results are encouraging considering the complexity of the problem, there are several points that are worthwhile to take note of:

- A basic assumption of this type of model is that the waste bed composition is uniform across the whole bed area. While this condition can be deemed satisfactory in carefully designed laboratory experiments, in a realistic incinerator this is difficult to be achieved. How the spatial variability in waste composition affects the waste bed incineration process and whether this influences the final gas output has not been well studied. The formulation above, however, can be easily modified to incorporate this spatial variation;
- The radiative heat flux from the furnace has been identified to be one of the key factors causing the temperature rise of the waste bed. The present model adopts the simple approach of using a radiative heat conductivity that is proportional to the temperature cubed to simulate the effect. Although we have shown that the model is able to predict the bed temperature profile reasonably well and can serve the objective, the model can be improved in the future by adopting more sophisticated formulations which are more stable and realistic with the empiricism reduced;
- The reaction mechanisms used in this study are drawn from several prior studies, which experiments involved different types of biomass. The reasonably good

agreement between the model predictions and experimental observations suggests that the model output is less sensitive to the accuracy of the reaction mechanisms being used;

- Eventually the waste bed model is developed to be coupled with the CFD model to compute the gases composition at the furnace exit. The exit gases composition not only depends on the waste bed, but also other factors, for example the configuration of the secondary overfire jet system. Yin *et al.* (2008) studied the effects of using different secondary overfire jet system. They found that while the jet system and the mesh had a significant effect on the flow pattern, temperature distribution, and hence exit gases composition, the waste bed model only affected mainly the region close to the bed. Thus, if the objective is mainly on the prediction of performance of the incinerator and the exit gases composition, the current simple model should be sufficiently accurate; and
- In this study, the test cases carried out were with specific types of biomass or organic material so that the model can be validated with the available experimental data in the literature. Sensitivity analysis is desirable to demonstrate the predictive ability of the model and bring insights to the incineration process. Here, we use two examples to demonstrate how biomass characteristics and operating conditions can affect the incineration process. In the first example, three typical biomass types of different density (chopped straw 80 kg/m³, hard wood chips 200 kg/m³, wood pellets 600 kg/m³, from McKendry (2002) are incinerated at the same operating conditions (initial bed height 1 m, furnace temperature 1100 K, primary air flow velocity 0.1 m/ s, temperature 300 K). Figure 12 shows the bed height reduction over time for all three cases. It can be seen that the chopped straw is quickly converted to volatiles and char since it has the lowest density (smallest mass with the same volume) out of the three cases. As the density of the biomass increases, the time required for the biomass bed to fall also increases. This may have implication to the speed of the incinerator grate that is operating at (to ensure sufficient time for the biomass to be incinerated). In the second example, the density of the biomass is kept at 100 kg/m^3 , but 3 different air flow velocities are tested: 0.02 m/s, 0.1 m/s, and 0.2 m/s; all other



Figure 12. Predicted bed height reduction over time for biomasses of different density

Waste bed incineration

operating conditions are the same as that in example one. Figure 13 shows the variation of oxygen consumed over time by various reactions in the incineration process. It can be seen the resulting oxygen consumption over time in all three cases have the same pattern – oxygen concentration drops quickly when the reactions start and goes back to the initial level when the reactions are completed. However, as the airflow increases, the drop in oxygen concentration reduces because the depleted oxygen is quickly replenished by the air supplied. This is also evident in the quicker rise in oxygen concentration after the reactions completed. This for example can help in determining whether the operation is over-supplying air – which wastes the energy in pumping.

5. Conclusions

A one-dimensional Lagrangian model for incineration waste bed has been developed in the present study. The changes in the bed mass because of drying, pyrolysis, devolatilization and char oxidation are accounted for explcitly using a number of established Arrhenius equations in the literature. The mass and concentration of O_2 , H_2O , CO, CO_2 , CH_4 and tar produced in the incineration processes and homogeneous reactions are also predicted by the model. The one-dimensional unsteady energy equations of solid and gas phases, which incorporate the furnace radiation, conduction, convection, and heat of reactions, are solved by the finite volume approach (Patankar, 1980) to yield the temperature profiles of both phases.

The developed model is validated by comparing the model predictions with the experimental observation of Goh *et al.* (2000) and Shin and Choi (2000). In general, the model can predict the temperature profile and waste bed height reduction reasonably well (generally within 20 per cent difference), considering that the process is complex and that the model is simplified in several ways – including the use of an Arrhenius equation to model the char oxidation process, the use of radiative heat conductivity to represent the radiative heat flux to the waste bed, the constant primary air velocity, and the uniformity of bed. The predicted gas concentration (O_2 and CO_2) are also compared with the experimental



Figure 13. Predicted oxygen concentration over time with different primary air velocity

HFF

29,2

observation. Overall, the depletion of oxygen and the rise of carbon dioxide level are reasonably well predicted by the model. The difference between the model prediction and observation is also generally within 20 per cent. The reasonable agreement indicates that the key processes of incineration have been captured. Subsequently, a sensitivity analysis is carried out to study the effects of different biomass density and airflow velocity. It is found that a denser biomass generally requires more time for the incineration process to complete and the waste bed height to fall; the time for the incineration process to complete must be considered when designing for the speed of the moving grate. The air velocity effect has also been studied. Increasing the air supply rate results in less oxygen concentration depletion during the reaction and quicker replenishment of oxygen after the reactions. The model can thus help in determining the air needed in the incineration process and avoid over-supplying air – which wastes energy in pumping.

Finally, it should be noted that quite often the performance of the incinerator and the furnace exit gases concentration are the main concerns. Yin *et al.* (2008) showed that the prediction of the exit gases concentration is more affected by the secondary overfire jet system configuration and the computational mesh, rather than the bed model used. As the objective of this study is to develop a model for the waste bed to couple with the computational CFD model of the furnace, the present model should be sufficiently accurate and efficient for this purpose.

References

- Basu, P. (2010), Biomass Gasification and Pyrolysis: Practical Design and Theory, Elsevier, New York, NY.
- Brosch, B., Scherer, V. and Wirtz, S. (2014), "Simulation of municipal solid waste incineration in grate firing systems with a particle based novel discrete element method", VGB Powertech, Vol. 1 No. 2, pp. 75
- Cordiner, S., Manni, A., Mulone, V. and Rocco, V. (2015), "Biomass furnace study via 3D numerical modeling", *International Journal of Numerical Methods for Heat and Fluid Flow*, Vol. 26 No. 2, pp. 515-533.
- Goh, Y.R., Yang, Y.B., Zakaria, R., Siddall, R.G., Nasserzadeh, V. and Swithenbank, J. (2000), "Development of an incinerator bed model for municipal solid waste incineration", *Combustion Science and Technology*, Vol. 162 No. 1, pp. 37-58.
- Goh, Y.R., Siddall, R.G., Nasserzadeh, V., Zakaria, R., Swithenbank, J., Lawrence, D., Garrod, N. and Jones, B. (1998), "Mathematical modelling of the burning bed of a waste incinerator", *Journal of the Institute of Energy*, Vol. 71 No. 487, pp. 110-118.
- Kaer, S.K. (2005), "Straw combustion on slow-moving grates-a comparison of model predictions with experimental data", *Biomass and Bioenergy*, Vol. 28, pp. 307-320.
- McKendry, P. (2002), "Energy production from biomass (part 1): overview of biomass", *Bioresource Technology*, Vol. 83 No. 1, pp. 37-46.
- Miljkovic, B., Pesenjanski, I. and Vicevic, M. (2013), "Mathematical modelling of straw combustion in a moving bed combustor: a two dimensional approach", *Fuel*, Vol. 104, pp. 351-364.
- Niessen, W.R. (2002), Combustion and Incineration Processes: Applications in Environmental Engineering, 3rd ed., CRC Press, Florida.
- Park, W.C., Atreya, A. and Baum, H.R. (2010), "Experimental and theoretical investigation of heat and mass transfer processes during wood pyrolysis", *Combustion and Flame*, Vol. 157 No. 3, pp. 481-494.
- Patankar, S.V. (1980), Numerical Heat Transfer and Fluid Flow, CRC Press, FL.

Waste bed incineration

HFF 29,2	Shin, D. and Choi, S. (2000), "The combustion of simulated waste particles in a fixed bed", <i>Combustion and Flame</i> , Vol. 121 Nos 1/2, pp. 167-180.
	Shin, D., Ryu, C.K. and Choi, S. (1998), "Computational fluid dynamics evaluation of good combustion performance in waste incinerators", <i>Journal of the Air and Waste Management Association</i> , Vol. 48 No. 4, pp. 345-351.
	Smoot, L.D. and Smith, P.J. (1985), Coal Combustion and Gasification, Plenum Press, New York, NY.
522	Sun, R., Ismail, T.M., Ren, X. and El-Salam, M.A. (2015), "Numerical and experimental studies on effects of moisture content on combustion characteristics of simulated municipal solid wastes in a fixed bed", <i>Waste Management</i> , Vol. 39, pp. 166-178.
	The World Bank (1999), "Municipal solid waste incineration", World Bank Technical Guidance Report.
	Wissing, F., Wirtz, S. and Scherer, V. (2017), "Simulating municipal solid waste incineration with a DEM/CFD method-influences of waste properties, grate and furnace design", <i>Fuel</i> , Vol. 206, pp. 638-656.
	Yang, Y.B., Sharifi, V.N. and Swithenbank, J. (2007), "Converting moving-grate incineration from combustion to gasification–numerical simulation of the burning characteristics", <i>Waste</i> <i>Management</i> , Vol. 27 No. 5, pp. 645-655.
	Yang, Y.B., Yamauchi, H., Nasserzadeh, V. and Swithenbank, J. (2003), "Effects of fuel devolatilisation on the combustion of wood chips and incineration of simulated municipal solid wastes in a packed bed", <i>Fuel</i> , Vol. 82 No. 18, pp. 2205-2221.
	Yang, Y.B., Phan, A.N., Ryu, C.K., Sharifi, V. and Swithenbank, J. (2006), "Mathematical modelling of slow pyrolysis of segregated solid wastes in a packed-bed pyrolyser", <i>Fuel</i> , Vol. 86 Nos 1/2, pp. 169-180.
	Yin, C., Rosendahl, L.A., Kær, S.K., Clausen, S., Hvid, S.L. and Hille, T. (2008), "Mathematical modelling and experimental study of biomass combustion in athermal 108 MW grate-fired boiler", <i>Energy</i> and Fuels, Vol. 22 No. 2, pp. 1380-1390.
	Zhou, H., Jensen, A.D., Glarborg, P., Jensen, P.A. and Kavaliauskas, A. (2005), "Numerical modeling of straw combustion in a fixed bed", <i>Fuel</i> , Vol. 84 No. 4, pp. 389-403.
	Further reading
	Kaer, S.K. (2004), "Numerical modelling of a straw-fired grate boiler", <i>Fuel</i> , Vol. 83 No. 9, pp. 1183-1190.
	Ryu, C., Shin, D. and Choi, S. (2001), "Effect of fuel layer mixing in waste bed combustion", <i>Advances in Environmental Research</i> , Vol. 5 No. 3, pp. 259-267.
	Ryu, C., Shin, D. and Choi, S. (2002), "Combined simulation of combustion and gas flow in a grate-type incinerator", <i>Journal of the Air and Waste Management Association</i> , Vol. 52 No. 2, pp. 189-197.
	Ryu, C., Yang, Y.B., Nasserzadeh, V. and Swithenbank, J. (2004), "Thermal reaction modeling of a large municipal solid waste incinerator", <i>Combustion Science and Technology</i> , Vol. 176 No. 11, pp. 1891-1907.
	Yu, Z., Ma, X. and Liao, Y. (2010), "Mathematical modeling of combustion in a grate-fired boiler burning straw and effect of operating conditions under air-and oxygen-enriched atmospheres", <i>Renewable Energy</i> , Vol. 35 No. 5, pp. 895-903.
	Corresponding author

Corresponding author Adrian Chun Hin Lai can be contacted at: adrianlai@ntu.edu.sg

For instructions on how to order reprints of this article, please visit our website: www.emeraldgrouppublishing.com/licensing/reprints.htm Or contact us for further details: permissions@emeraldinsight.com