Modeling of Waste-to-Energy Combustion with Continuous Variation of the Solid Waste Fuel

MASATO NAKAMURA, HANWEI ZHANG, KARSTEN MILLRATH AND NICKOLAS J. THEMELIS
Earth Engineering Center, Columbia University and
Waste-to-Energy Research and Technology Council, New York, NY 10027

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Abstract
A mathematical model of a mass-burn, waste-to-energy combustion chamber has been developed that includes stochastic representation of the variability of the fuel (municipal solid waste, MSW). The drying, pyrolysis, gasification and combustion processes on the moving grate are governed by several factors such as proximate and ultimate analysis, particle size, moisture, heating value, and bulk density, all of which change continuously. This extreme variability has not been considered in past mathematical models of WTE combustion that used mean values of the MSW properties. The Monte Carlo stochastic method has been applied to provide a time series description of the continuous variation of solid wastes at the feed end of the traveling grate. The combustion of the solid particles on the grate is simulated using percolation theory. The feed variation and the percolation theory models are combined with the FLIC two-dimensional bed model developed by Sheffield University to project the transient phenomena in the bed, such as the break-up of waste particles and the channeling of combustion air throughout the bed, and their effects on the combustion process.

1. Introduction
Unstable combustion in a mass-burn chamber is one of the major problems caused by the variability of municipal solid waste (MSW). One reason for the instability of combustion is its extreme variability of the properties of the feedstock. MSW is more
complex and non-homogeneous than most fossil fuels. The physical and chemical properties of MSW directly affect its combustion. Another reason for unstable combustion of MSW is transient phenomena such as the break-up of waste particles and the channeling of combustion air. The resulting unstable combustion of MSW introduces operating difficulties such as fluctuating chamber temperature, low thermal efficiency of the combustion chamber and formation of undesirable compounds (CO, NOₓ, and dioxin) in the process gas of waste-to-energy (WTE) facilities.

Some advanced automatic combustion control systems for mass-burn plants have been developed worldwide to stabilize the condition during combustion. For example, Infrared Radiation (IR) sensors are provided in the advanced control systems for image processing and detection of burn out lines [1]. Also, an auto-regressive model with periodic functions (fuzzy logic) is used in chaos analysis for continuous variation of MSW in the control system. It provides good control performance for reducing concentration of CO, NOₓ and dioxins.

Although these new tools have resulted in improved control and operating performances, the continuous variation of the MSW feed into the combustion chamber still makes control of the combustion process difficult. The existing combustion models for mass-burn MSW chambers have used mean values for physical and chemical properties of MSW components, such as proximate analysis and Higher Heating Value (HHV). In this study, a mathematical model for time series analysis of continuous variation of MSW has been developed using the Monte Carlo method to simulate stochastic combustion. Additionally, a percolation theory is applied in order to simulate transient phenomena.

2. Modeling

This study presents a time series model for continuous variation of MSW using the Monte Carlo Method. Table 1 shows percentages of MSW components and the approximate analysis of various types of combustible dry waste materials in New York City. They are used in this model as an initial distribution. The probability distribution of components of MSW for a uniform distribution $U_k \sim U(0, 1)$ is given by
In order to carry out the computation for the components of MSW, the MATLAB 6 program is used to generate 100 random numbers \((k=100)\) for each of 100 samples \((n=100)\).

The FLIC two-dimensional bed program [2] developed by Sheffield University was used, in conjunction with our model for continuous variation of MSW, in order to simulate the combustion process. The FLIC program is used to calculate the fluid flow, heat transfer and combustion reactions in both gaseous and solid phases.

Also a model for transient phenomena was developed, based on the percolation theory in this study. The first percolation model, by Broadbent and Hammersley (1957) [5], was primarily concerned with the existence of the ‘open path’ in a system, in which a large porous stone is immersed in a bucket of water. It has been claimed that percolation theory is a cornerstone of the theory of disordered media, and provides a reasonable model for a disordered medium such as MSW. Although there are two types of percolations \((\text{bond percolation and site percolation})\), in this study, we will consider site

\[
X_k \sim \begin{pmatrix}
\text{Paper} & \text{Cardboard} & \text{Plastics} & \text{Textiles} & \text{Rubber & Leather} & \text{Wood} & \text{Glass} & \text{Metals} & \text{Other} \\
0.266 & 0.047 & 0.089 & 0.047 & 0.002 & 0.022 & 0.05 & 0.048 & 0.046
\end{pmatrix}.
\] (1)

**Table 1 Ultimate analysis of dry stream municipal solid wastes in New York City [3, 4]**

<table>
<thead>
<tr>
<th>Component of waste stream</th>
<th>% in NYC</th>
<th>Weight (metric tons day)</th>
<th>Carbon (% by Weight)</th>
<th>Oxygen (% by Weight)</th>
<th>Nitrogen (% by Weight)</th>
<th>Sulfur (% by Weight)</th>
<th>Ash (% by Weight)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Paper</td>
<td>26.6</td>
<td>3144</td>
<td>43.5</td>
<td>6</td>
<td>44</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Cardboard</td>
<td>4.7</td>
<td>555</td>
<td>44</td>
<td>5.9</td>
<td>44.6</td>
<td>0.3</td>
<td>0.2</td>
</tr>
<tr>
<td>Plastics</td>
<td>8.9</td>
<td>1052</td>
<td>60</td>
<td>7.2</td>
<td>22.8</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Textiles</td>
<td>4.7</td>
<td>555</td>
<td>55</td>
<td>6.6</td>
<td>31.2</td>
<td>4.6</td>
<td>0.2</td>
</tr>
<tr>
<td>Rubber &amp; Leather</td>
<td>0.2</td>
<td>24</td>
<td>69</td>
<td>9</td>
<td>5.8</td>
<td>6</td>
<td>0.2</td>
</tr>
<tr>
<td>Wood</td>
<td>2.2</td>
<td>260</td>
<td>49.5</td>
<td>6</td>
<td>42.7</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Glass</td>
<td>5</td>
<td>591</td>
<td>0.5</td>
<td>0.1</td>
<td>0.4</td>
<td>&lt;0.1</td>
<td>-</td>
</tr>
<tr>
<td>Metals</td>
<td>4.8</td>
<td>567</td>
<td>4.5</td>
<td>0.6</td>
<td>4.3</td>
<td>&lt;0.1</td>
<td>-</td>
</tr>
<tr>
<td>Other</td>
<td>4.6</td>
<td>544</td>
<td>26.3</td>
<td>3</td>
<td>2</td>
<td>0.5</td>
<td>0.2</td>
</tr>
<tr>
<td>Tons per day</td>
<td>7292</td>
<td>2865</td>
<td>372</td>
<td>2194</td>
<td>42</td>
<td>10</td>
<td></td>
</tr>
</tbody>
</table>
percolation for transient phenomena in combustion. There are a number of network models such as Honeycomb, Square, Kagome, Triangular, Diamond, Simple Cubic, BCC and FCC. A network of MSW on the traveling bed of combustion chamber is specified in the model as a two-dimensional square lattice (Figure 1) in order to simplify the combustion process. The lattice size $L$ was defined as 40 (40 x 40) for the same reason. We designate each vertex of the lattice $\mathbb{Z}^2$ open with probability $p$ and closed otherwise. $p_c$ is the critical probability and is defined by

$$p_c = \sup \{ p : \Theta(p) = 0 \}. \quad (2)$$

*Figure 1. Two-dimensional square lattice site percolation model used in the solid waste on the combustion grate*
The current estimate of this critical probability $p_c$ for site percolation in the two-dimensional square lattice is 0.5927 [6]. We assume that combustion in the lattice proceeds uniformly. The program code for this model was developed using Visual Basic. Figure 2 shows the break-up and channeling of MSW on the combustion grate. Break-up usually occurs when particles in the middle of the solid waste burn horizontally as shown in Figure 2(a). This means that at least one cluster reaches both horizontal edges of the lattice in the percolation model. Channeling, on the other hand, usually occurs when particles of solid waste burn vertically as shown in Figure 2(b). This means at least one cluster reaches both vertical edges of the lattice [7].

In our model we specified the use of the Martin Reverse Acting Grate (Figure 3), one of the most popular WTE grates used in the United States. The MSW fed on this grate travels approximately 7.0 m in an hour. We divided the grate into 8 zones, through which MSW runs continuously. Mixing coefficients are assumed to be zero in order to simplify motion of the solid waste. The simulations have been performed on a Linux
computer (CPU: 1.8MHz, Memory: 256MB) with VMware for Windows 98 environment. It takes approximately two hours to complete one set of the calculations for this model.

3. Results and Discussion

Figure 4 shows the simulation results for continuous variation of the components of MSW generated in New York City. The abscissa shows the MSW sample number. Each sample has several components and, together, they define a time series for continuous variation of MSW. The first 20 of the 100 samples used are shown in Figure 4. The time series made by these samples specify one of the initial conditions to simulate the combustion process.

The simulation results using the above samples are shown in Figure 5. The solid temperature is highest in the middle of the grate which is located around Zone 4, as shown in Figure 5 (a). Near the inlet of the combustion chamber, temperatures of solid
waste remain under 371 K because moisture evaporation occurs in this stage and combustion of most components of MSW is limited. Figure 5 (b) shows the residual ash in solid (mass %). From the middle of the grate to the ash discharge end of the grate, the MSW burns well and generates ash until it reaches the burn-out line, which is in Zone 8. Figure 5 (c) shows the simulation results of percolation model for transient phenomena (break-up and channeling). It is based on the calculation result of residual ash shown in Figure 5 (b). From Zone 5 to Zone 8, each combustion probability is nearly equal to or exceeds the critical probability $P_c$. This indicates that the possibility of break-up and channeling of solid waste after Zone 5 is high, and channeling is observed in the lattice of Zone 5.

Figure 6 shows how much combustion is completed by volume % in the each zone. We assumed that MSW from inlet of the chamber consists of 20 % volumetric
voids, i.e., $P_v = 0.2$. Therefore, for example, solid waste in Zone 1 burns only 13 volume % of total solid waste. The most important combustion phenomena and their

(c) Result of percolation model for transient phenomena (break-up and channeling)

Figure 5. Calculation results of the MSW combustion on the Martin grate
most probable occurrences are shown in Figure 7. In this study, we assumed \( P_v = 0.2 \). \( P_c \) is 0.5927 because we specified a square lattice for this percolation model. \( P_{ch} \) is the channeling probability and, between \( P_c \) and \( P_{ch} \), channeling is generated frequently. \( P_a \) is the ash probability. This means the burn-out line which means the remaining solid waste does not contain combustible matter. Break-up occurs between \( P_{ch} \) and \( P_a \).

![Figure 6. Combustion probability in the each zone](image)

\[ \Theta(p) \]

![Figure 7. Transient phenomena during the combustion processes](image)
4. Conclusion

The simulation results of this combustion model with continuous variation of MSW have provided the temperatures and percentage of residual ash by weight. From that, the volume change (%) from waste to ash have been calculated and the combustion probabilities for each zone have been estimated. The percolation model has shown the mechanism of transient phenomena such as channeling and break-up of solid waste. The governing parameters such as void probability $P_v$, channeling probability $P_{ch}$, critical probability $P_c$, and ash probability $P_a$ were found by this model.

The first results obtained are very promising and it is hoped to gain a better understanding of the governing combustion and mixing mechanism with the Monte Carlo method. Further research work is needed to investigate in great detail aspects of gas generation caused by physical and chemical properties in this model. Also, a more precise and intricate network in the percolation model will be required to simulate the frequency of transient phenomena.

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References