Flow simulations have been carried out to evaluate the effects of combustion chamber design and air/combustion gas flow configuration on the overall performance of municipal solid waste incinerators. Computational results show velocity and temperature fields in the entire region of flow passage. Local recirculations and uneven distributions of flow velocity and temperature should be minimized and mixing is to be enhanced. Two parameters are proposed to help quantify the overall flow condition. The degree of mixing of different species, which enter the incinerator from the air and combustion gas inlets, is represented by the mixing parameter $\alpha$. Here, $\alpha$ is calculated on the nodal points. The probability distribution of $\alpha$ in the entire computational domain is used for comparative evaluation of incinerator designs. The thermal decomposition parameter $\beta$ is calculated by integrating the kinetic rates along the trajectory of a fluid element. This parameter represents the portion of the unreacted materials among the total pollutants released from the bed. By employing these parameters, various incinerator design alternatives can be quantitatively analyzed from two principal viewpoints, i.e., the effectiveness in mixing and the thermal decomposition of pollutants.

**INTRODUCTION**

Incineration is an attractive method to process safely municipal solid waste. Recently, attention is focused on the issue of minimizing the pollution associated with the incineration process. To reduce the emission of combustion-generated pollutants, sophisticated flue gas emissions control devices are added, but the first priority is to minimize the formation itself and destroy the produced pollutants. To achieve these goals, combustion control strategies have been formulated and they are adopted as national codes in some countries [1–3].

Design requirements of high-performance incinerators are sometimes summarized as the achievement of 3Ts (time, temperature, and turbulence). An adequate retention time in hot environment is crucial to destroy the products of incomplete combustion and organic pollutants. Also turbulent mixing enhances uniform distributions of temperature and oxygen availability. In this context, the design of a combustion chamber, in which air and combustion gases pass through while participating in strong radiative heat transfer, must be carefully analyzed and evaluated.

Various chamber designs and air/gas flow arrangements have been proposed and tested in actual field applications. Comparative evaluation of furnace chamber designs often relied on cold flow experiments using two-dimensional water tables [4], and/or three-dimensional cold air flow models [5]. However, even these scale model experiments are expensive and are limited in their applicability. On the other hand, numerical computation has rapidly become available by adequately accommodating the complex geometry and flow conditions in incinerators. Numerical flow simulations now enable detailed parametric variations of design variables, and some recent attempts for incinerator flow analysis are reported. Ravichandran and Gouldin performed numerical simulation of cold flow in a mass-burn municipal waste incinerator to examine the effects of the secondary air [6]. They showed how the overfire air enhanced the mixing inside the combustion chamber. Kitamura et al. compared the numerical results with experiments to study the effects of the secondary and tertiary air on the overall combustion efficiency for a simulated fluidized-bed type municipal waste incinerator [7]. Nasserzadeh et al. scrutinized the
flow simulation and suggested a modified design, which would improve the combustion efficiency and heat transfer rate to the water wall of the combustion chamber [8, 9]. They argued that the incinerator performance could be improved by eliminating the recirculation zone in the secondary combustion chamber. Ide et al. changed the air flow passage arrangement in order to allow the pollutant products generated from the drying zone of the combustion bed to mix with the hot combustion gas [10]. Additional mixing was required for effective thermal decomposition of organic pollutants and unburned substances.

The present study reports on a critical assessment of design alternatives in the combustion chamber and air/combustion gas flow configuration. The maximum destruction of pollutants inside the furnace is the main objective; therefore mixing of the cold air and hot gases and subsequent pyrolysis reaction of hypothetical organic pollutants are to be investigated. Numerical simulations of the flow field inside the combustion chamber provide velocity, temperature and concentration data at the nodal points of computational grids. In an effort to accomplish quantitative measures of performance, two parameters are introduced to help quantify the overall flow conditions in terms of mixing and subsequent reaction.

**INCINERATOR DESIGN ALTERNATIVES**

Various design alternatives have been tested, because the geometric shape of combustors as well as the air and gas flow arrangement crucially affect the incinerator performance. Shown in Fig. 1 are three types of municipal waste incinerator combustion chamber. Figure 1a is classified as a counter flow type, while Fig. 1c as a parallel flow type. Figure 1b displays a modified counter flow type, where a furnace neck is supposed to increase the mixing and to augment the radiative heat transfer to the combustion bed in the primary combustion chamber. Since each of these combustor configuration has been discussed with pros and cons, they are selected as test cases [10, 11].

In addition to the geometry of combustion chamber, the air and gas flow arrangement is also important. The primary combustion air (underfire air), which is fed underneath the combustion bed, is divided into several (at least three) regions, so that an adequate amount of

![Fig. 1. Three selected geometries for numerical simulation: (a) a counter flow type incinerator (geometry C); (b) a modified counter flow type incinerator (geometry C'); (c) a parallel flow type incinerator (geometry P).](image-url)
air is delivered to the respective zone in the bed. The secondary air (overfire air, OFA) is used to increase the mixing inside the combustion chamber. The total air supply is usually set at 1.5–2.0 times the stoichiometric requirement, and the relative distribution of air into the subdivisions of primary air and secondary air jet nozzles can influence the combustion performance. Table 1 summarizes the percentage air distribution of the cases reported in this paper.

NUMERICAL METHOD

The flow field within the combustion chamber is highly turbulent and three-dimensional. In this study, however, the combustion chamber modeling is simplified and limited to a two-dimensional geometry. Two-dimensional models allow a much simpler treatment, while a good deal of the physical significance may be retained. For example, computational results of a grate-type incinerator by Nasserzadeh et al. [8] showed a strong two-dimensionality of the flow field. Moreover, the cross-flow pattern, which is seen in the mixing region of overfire air jet and combustion gas flow from the primary combustion region, can be characterized as two-dimensional for $s/d < 10$, where $d$ is the diameter of a nozzle and $s$ is the distance between the adjacent nozzles [12]. For a typical MSW incinerator of 300 ton/day capacity, $d$ is larger than 35 mm and $s$ is larger than 320 mm in the combustion chamber of $3.5 \times 6$ m.

In this account, the flow field, temperature distribution, and mixing of the designated gaseous elements are simulated by using FLUENT, a commercial code utilizing the SIMPLE method [13]. The standard $k$–$\varepsilon$ turbulence model, which is widely employed in thermal flow analyses, is adopted for the prediction of turbulence phenomena [14]. In the combustion zone of the grate, the wastes are in flame at above 1000°C, and the radiation is the main heat transfer mode. For the radiation model, the gas within the chamber and the walls are assumed to be gray, having uniform absorptivity and emissivity over the range of all wavelengths. The discrete transfer radiation model (DTRM), utilizing the ray-tracing technique, is adopted. The gravity force to give rise to buoyancy phenomena is also included.

The computational mesh is formed by $60 \times 70$ nodes, which are clustered near the walls and overfire air injection jets where the velocity gradients are high. Since most of the combustion is completed over the grate, chemical reaction is not considered in the computational domain. The combustion product gases are treated as input gases. The inlet boundary conditions at the grate, illustrated in Table 2, such as the composition of the gas, temperature and flow rate, are prescribed by referring to the direct measurement data of Santos [15]. Uniform flow conditions are specified as the boundary conditions for the four underfire air inlet zones, and jets of 50 m/s are prescribed as the overfire air inlet boundary conditions. The wall temperature is fixed at 220°C, which is to represent the evaporation at the 1.6 MPa membrane water wall. A free boundary condition is enforced at the exit of combustion chamber. The pressure inside the combustion chamber is atmospheric.

VELOCITY AND TEMPERATURE FIELDS

Typical results of numerical calculations can be represented by the velocity vector plot and temperature contour plot, as displayed in Figs. 2a and 2b for Case C1 and Figs. 3a and 3b for Case P1. Velocity vector field plots identify the recirculation of flow and the velocity nonuni-

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
<tr>
<td>COMBUSTION AIR INPUT DISTRIBUTIONS OF NUMERICAL SIMULATION CASES (UNIT:%)</td>
</tr>
<tr>
<td>Case</td>
</tr>
<tr>
<td>Geometry</td>
</tr>
<tr>
<td>Under Drying zone</td>
</tr>
<tr>
<td>Primary combustion zone I</td>
</tr>
<tr>
<td>Primary combustion zone II</td>
</tr>
<tr>
<td>After-burning zone</td>
</tr>
<tr>
<td>Overfire air</td>
</tr>
<tr>
<td>b</td>
</tr>
<tr>
<td>c</td>
</tr>
</tbody>
</table>
TABLE 2
Inlet Boundary Conditions (Two-Dimensional)

<table>
<thead>
<tr>
<th>Cases</th>
<th>C1, C', P1</th>
<th>C2, C3, P2, P3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Temp. (K)</td>
<td>Species Flow Rate (mole/s unit depth)</td>
</tr>
<tr>
<td></td>
<td>CO₂</td>
<td>H₂O</td>
</tr>
<tr>
<td>Under fire air</td>
<td>Dry. zone</td>
<td>841</td>
</tr>
<tr>
<td></td>
<td>Prim. comb. zone I</td>
<td>1485</td>
</tr>
<tr>
<td></td>
<td>Prim. comb. zone II</td>
<td>1295</td>
</tr>
<tr>
<td></td>
<td>After-burn. zone</td>
<td>945</td>
</tr>
<tr>
<td>Over fire air</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

formity, especially near the geometric irregularities such as turns or noses. Sometimes the Lagrangian particle tracking principle can be applied to demonstrate the simulated particle streaklines, which determine the residence time of the flow elements in the furnace. Portrayed in Fig. 4 are the examples of the turbulent path lines of combustion gases for Cases C1 and C2.

The velocity vector plot is useful in validating the simulation results against the experimental observations. Cold flow tests using a two-dimensional water table or a scale model of isothermal flow are effective. In our previous tests [4], the simulation results showed reasonable resemblances in the flow field, but minor adjustments were necessary to match the size and location of the recirculation zones of the flow. The temperature field plot is helpful in understanding the nonuniform temperature distribution inside the furnace. The temperature distribution indicates the mixing

![Fig. 2. Velocity vector and temperature contour plot for a counter flow type incinerator (Case C1): (a) velocity vector (a half densed plot in y direction); (b) temperature contour (K).](image)

![Fig. 3. Velocity vector and temperature contour plot for a parallel flow type incinerator (Case P1): (a) velocity vector (a half densed plot in y direction); (b) temperature contour (K).](image)
The bed contains partially burned substances. The overfire air is intended to mix these combustion gases with fresh air, which will create an adequate temperature and oxygen conditions to enhance subsequent oxidations. Turbulence plays an important role, but the resultant mixing is of major concern.

Ravichandran and Gouldin [6] investigated the degree of mixing by numerically calculating the concentration of tracer gases. The overfire air is treated as a different species, as compared with the combustion gases produced by the underfire air. An equiconcentration contour plot may be constructed from the results, but comparative evaluations of the computational results cannot be quantified. If one wants to check the mixing of several different species originating from different regions of the bed, the situation becomes even more complicated.

In an effort to quantify the degree of mixing, a mixing parameter was proposed. This concept was applied to cold flow simulations [4], and it is now extended for the non-isothermal cases. The parameter for a given location is defined as

$$\alpha = \sqrt{\frac{\sum_{j=1}^{N}(X_j - X_{j0})^2}{2}},$$

where $X_j$ is the local mass fraction ($m_j/\sum_{i=1}^{N}m_i$) of the $j$th tracer and $X_{j0}$ is the mass fraction under the completely mixed condition. The parameter sums up the deviations of local concentration for each of the $N$ constituents. As all the constituent elements become completely mixed, $\alpha$ approaches zero. The parameter value of $\alpha$ at a given location represents the degree of non-mixing.

**Mixing and Thermal Decomposition Parameters**

**Mixing Parameter**

The importance of mixing in mass burn incinerators is well recognized. The underfire air is delivered to the waste bed over the grate, and it produces combustion gas, with variable compositions and temperatures. In most cases, the gas from the drying region is high in moisture content and low in temperature, and it contains incomplete combustion products. The combustion gas from the main burning zone of

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![Combustion gas trajectory plot for counter flow type incinerators: (a) case C1; (b) case C2.](image-url)
when the wastes are in or near the drying zone of the combustion bed, where vaporization and pyrolysis reaction take place. To minimize emission of the toxic organics, released pollutants must be destroyed by sufficient thermal decomposition. Table 3 lists the thermal decomposition characteristics of some of the suspected pollutants which can be emitted in the incineration process [16]. The kinetic parameters are derived, which are based on a one-step Arrhenius type reaction of zeroth order on oxygen concentration with the activation energy $E$ and preexponential factor $A$:

$$\frac{dC_j}{dt} = -k'C_j,$$

where

$$k' = A \exp(-E/RT).$$

The decomposition rates of dioxin and furan are known to be larger (faster) than those of benzene and dichloromethane. $T_{99}$ in Table 3 denotes the temperature at which 99.99% of a given species is decomposed within 1 s. $T_{99}$ of dioxin or furan is around 1100 K.

Now that the destruction of pollutants (thermal decomposition) is a combined result of time and temperature, a new parameter $\beta$ is introduced, which quantitatively expresses the nonreactedness of a given pollutant:

$$\beta = \frac{C_{ji}}{C_{je}} = \exp\left(-\int_{inlet}^{exit} Ae^{-E/RT} dt\right),$$

where $C_{ji}$ and $C_{je}$ are the concentrations of species $j$ at the inlet (the grate) and exit (the furnace outlet), respectively. The smaller values of $\beta$ mean a more complete destruction of pollutant species $j$. This equation is derived by integrating Eq. (2) along a trajectory of a fluid element. The particle tracking method is applied to find the trajectories of pollutant elements emitted from the grate in much the same manner as in Nasserzadeh et al. [9]. Here, the turbulent fluctuation components $u'$ and $v'$ have the following forms:

$$u' = \xi_1 \left(\frac{2k}{3}\right)^{1/2}, \quad v' = \xi_2 \left(\frac{2k}{3}\right)^{1/2}$$

where, $\xi_1$ and $\xi_2$ are normally distributed random numbers, and, $k$ is turbulent kinetic energy. It is further assumed that the values $\xi_1$ and $\xi_2$ are retained for the time interval $\tau$, which is the characteristic lifetime of an eddy, defined as

$$\tau = \frac{C_{\mu}^{3/4} k}{2^{1/2} \varepsilon},$$

where, $\varepsilon$ is turbulent kinetic energy dissipation rate. For a given position, the mean velocity, $k$, $\varepsilon$, and temperature are interpolated from the values at the four surrounding node points.

### RESULTS AND DISCUSSION

Typical contour plots of the mixing parameter $\alpha$ for Cases C1 and P1 are depicted in Figs. 5a and 5b. In this case, the identifiable gases selected are H$_2$O, CO$_2$, O$_2$, and N$_2$. The relative concentrations of these constituents vary for each of the grate locations and overfire air inlet. For example, the overfire air is pure air (containing only N$_2$ and O$_2$), and the gas from the drying zone of the grate contains a high level of H$_2$O, but very little of CO$_2$ with the remainder in N$_2$ and O$_2$. As can be seen in the figures as stiff gradients of contour lines, unmixed gases coming out from the drying zone experience vigorous mixing. Since identical inlet conditions are given for Cases C1 and P1, the $\alpha$ values near the grate are similar. It is easily seen that furnace geometry strongly affects the flow. Case P1 shows much faster mixing compared to Case C1. The results of Case P1 show strong mixing in the primary
It is clear that the overfire air enhances mixing significantly (compare Case C1 with Cases C2 and C3, and compare Case P1 with Cases P2 and P3, respectively). The injection angle of the overfire air has a significant influence on the mixing characteristics, too. The parallel flow type incinerators yield smaller values of mixing parameter than the counter flow type incinerators. This may imply that the radiation panel in the parallel flow type incinerator alters the flow field in such a manner to improve mixing. Meanwhile, the modified shape C1, where the primary combustion zone is enclosed by a neck-shaped furnace wall, presents an improved mixing state compared to the base Case C1. It is believed that the modified geometry enables an increased mixing of gases from the drying zone with the gases from the combustion zone.

The thermal decomposition parameter $\beta$ is evaluated for a volume element of pollutants along its trajectory. Since the particle trajectory is determined by the local turbulent velocity component with statistical randomness, the particles liberated from the identical location may follow different paths and their respective thermal decomposition parameter may vary. By statistically averaging the parameter values (typically 10000 trials) for the particles generated from a given inlet (grate) location, the thermal decomposition behavior of pollutants released from the location can be inferred. Since the behavior of gases liberated from the drying zone of the grate is important in regard to the pollutant emission, the $\beta$ values with respect to the designated position of the drying zone are calculated. By using the kinetic rates of Table 3, the $\beta$ values for chlorobenzene are shown in Fig. 7 and for chloroform in Fig. 8. The $x$ position in the abscissa represents the distance from the starting point of the grate. The pollutants released from the entrance region tend to remain unreacted. For example, 30%–60% of the unreacted chlorobenzene will leave the furnace if it were released at the immediate inlet of the grate. Thermal decomposition of chloroform is more sensitive to the combustion chamber design. Figure 8 indicates that the $\beta$ values are several orders of magnitude different in alternative designs. The effect of overfire air on the destruction of pollutant...
organics can be seen by comparing Case C1 to Cases C2 and C3 and by comparing Case P1 to Cases P2 and P3, respectively. The injection angles of overfire air jets are found to be important (compare Cases C2 and P2 with C3 and P3). Case C'1 shows improvement over the base Case C1.

By multiplying $\beta$ with the fractional mass flow rates and summing over the drying zone of the grate, the averaged value $\bar{\beta}$ is obtained. This parameter signifies the overall ratio of pollutants that have been released from the grate and can escape undecomposed from the furnace, under the assumption that the release

Fig. 6. Probability density distributions of mixing parameter $\alpha$ of each simulation case.
of pollutants is proportional to the mass flow rate of the underfire air. Shown in Fig. 9 are values of $\bar{\beta}$ for the test cases. It is seen that thermal decomposition of chloroform is much easier than that of chlorobenzene. By using this simple quantitative parameter, comparative evaluation of alternative designs is straightforward. We see that the overfire air injection give favorable effects on reducing the pollutant emission (compare Case C1 to Cases C2 and C3 and compare Case P1 to Cases P2 and P3, respectively). In general, parallel flow designs are more effective in thermal decomposition.

Comparing $\bar{\beta}$ values to $\bar{\alpha}$ values for selected test cases, the trend appears to be similar. This implies a close correlation between the degree of mixing and the thermal decomposition. It is interesting to note that mixing of gaseous constituents will result in more uniform temperature distribution.

**LIMITATIONS**

Numerical simulation results enabled a quantitative evaluation of combustion chamber design alternatives, but the modeling is not free from limitations. Some of the major uncertainties may be related with the assumptions, such as the two-dimensionality, turbulence model, input conditions (temperature, gaseous concentrations, velocity), simplified model geometry etc. For example, the secondary air jet in the real incinerators differs much from the two-dimensional slot jet, and this will result in serious discrepancies. The current attempt of
CONCLUSIONS

Good combustion performance of incinerators can be summarized to achieve maximum destruction of toxic organics by providing high degrees of mixing in the combustion chamber. The mixing is designed to allow the intermediate combustion products to undergo the decomposition and subsequently the complete oxidation. To meet these requirements, various combustion chamber geometries and overfire/underfire air distribution schemes have been appraised. In evaluating these design alternatives, numerical simulations are attractive in terms of saving time and costs. Flow simulations of a furnace usually provide the velocity vector and temperature field data in the computational domain. The global flow patterns, irregularities such as the recirculation zone, and mixing tendency (based on the temperature distribution) could be qualitatively evaluated. In such cases, however, the experienced engineer’s perception of good performance is essential.

A mixing parameter $\alpha$, which represents the degree of unmixedness of different species, is found to be useful in quantitatively evaluating the mixing. A thermal decomposition parameter $\beta$ is calculated by statistically summing up the ratio of unreacted pollutants which have been released from the bed and subsequently allowed to pass through the flow passage. It can be used to express the condition of the combustion environment inside the furnace.

Selected sets of incinerator designs were analyzed by employing the above-stated newly defined parameters. The degree of mixing was influenced by the overfire air jet velocity (the magnitude and the direction) and by the geometric configuration of the combustion chamber. The thermal decomposition of pollutants was also investigated by employing a kinetics
model. The time and temperature history of a flow element was incorporated into a single parameter. The thermal decomposition parameter for the chosen incinerator design alternatives also demonstrated the effect of chamber geometry and air/gas flow passage arrangement. The designs of better performance in mixing showed a more effective thermal decomposition. Based on these quantitative comparisons, superior design alternatives can be selected, when other parameters such as cost, material selection and operational convenience are also included for a final consideration.

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