Numerical simulation study on bed combustion of waste incinerator in the severe cold region

Hongze Zhang[1,2,*]
[1]Guangxi Key Laboratory of Machine Vision and Intelligent Control, Wuzhou University, Wuzhou, China
[2]School of Electronic Information and Artificial Intelligence, Wuzhou University, Wuzhou, China

Corresponding author: Hongze Zhang (e-mail: hzzhang1981@163.com)

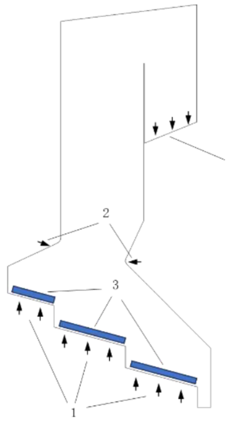
ABSTRACT To optimize the layer combustion effect of the waste incinerator in the severe cold region, the numerical simulation of a 750t/d waste incinerator in the severe cold region in the three northeastern provinces of China was conducted based on the FLIC software. The simulation results show that the combustion process of waste can be roughly divided into three stages along the grate's movement direction: which are the water evaporation stage from 0m to 8.8m, the volatile emission and combustion stage from 2m to 10m, and the fixed carbon ignition and burnout stage from 2.1m to the grate's outlet. Due to the high moisture content of the waste in the three eastern provinces, the bed's height significantly decreases after the water evaporation. Because the ignition position of the fixed carbon is behind, the combustion rate of the fixed carbon is low. The primary air temperature can be appropriately increased, and the primary air distribution ratio can be optimized. In order to improve the combustion efficiency, it is recommended that the drying section provides 10 % of the total primary air volume, the volatile emission and fixed carbon combustion section provides 70 % of the total primary air volume, and the fixed carbon burnout section provides 20 % of the total primary air volume. In order to solve the problem of low fuel temperature at the grate's inlet, the direct air preheater should be used to preheat the waste before it enters the furnace to advance the ignition position of the fixed carbon and improve the burnout rate of the waste. Adjusting the angle of the front and rear arches to enhance the furnace's radiation intensity and ignition effect is recommended to accelerate the combustion speed of the waste. It is suggested that the furnace be fully insulated to reduce the heat loss and improve combustion efficiency. According to the simulation results, an optimization strategy is proposed for the operation and structure of the incinerator to achieve the purpose of optimizing combustion.

INDEX TERMS Severe cold region; Waste incinerator; Bed combustion; Numerical simulation

I. INTRODUCTION

With the continuous advancement of China's urbanization process, the per capita output of municipal solid waste (MSW) has increased yearly. Domestic waste contains toxic substances, such as mercury, cadmium, and lead, which will seriously pollute the environment if not handled properly. The primary ways to deal with domestic waste are landfills, composting, and incineration. Landfill occupies much land around the city, and composting efficiency is low. Therefore, China advocates waste incineration. Waste incineration can turn domestic waste into inert residues with stable properties and low environmental harm. It can significantly reduce the volume and weight of domestic waste and generate heat and electricity. The moisture and ash content in China's domestic waste is high [1], and the waste's LHV is proportional to the urban economy [2]. The weather in the three northeastern provinces of China is cold, and their economy has a particular gap with the developed eastern coastal areas. The content of kitchen waste in their domestic waste exceeds 50 %, and the moisture content exceeds 55 %, so the LHV is low.

Many scholars have conducted in-depth simulation studies on the incineration characteristics of waste. Yang et al. [3]–[5] proposed the control equations of the waste bed combustion. Ma et al. [6] studied a 450t/d MSW incinerator and pointed out that the distribution ratio of the primary air chambers will affect the furnace temperature, gas-phase combustion, and flow field distribution in the incinerator. Qu [7] took a 350t/d waste incinerator at a high altitude as the research object and pointed out that the combustion performance of the incinerator can meet the '3T' criterion. Zhang et al. [8] compared the simulation results of a 500t/d grate incinerator in Lhasa with the actual test data, and the correctness of the combustion simulation method of the incinerator was verified. Lin et al. [9] analyzed the effects of different structures of a 350t/d waste incinerator in



1. primary air. 2. secondary air. 3. waste bed. 4. furnace outlet.

Fig. 1. The schematic diagram of the grate incinerator.

Guangdong on the combustion characteristics of the furnace. Yang et al. [10] proposed an optimal selective non-catalytic reduction (SNCR) process parameter for a 500t/d waste incinerator. Zeng et al. [11] studied a 450t/d grate incinerator and pointed out that increasing the co-incineration ratio of stale waste will end the waste incineration process in advance and reduce the rate of water evaporation, volatile release, and fixed carbon combustion.

FLIC (Fluid Dynamic Incinerator Code) is a two-dimensional bed combustion simulation software developed by Yang et al. [3]. Based on Yang's bed model, the FLIC software is used to simulate the bed combustion of a waste incinerator in the severe cold region in the three northeastern provinces of China.

II. STRUCTURE AND FUEL CHARACTERISTICS OF THE WASTE INCINERATOR

The research object of this paper is an MSW grate incinerator in the severe cold region of the three northeastern provinces of China with a treatment capacity of 750t/d. The incineration plant is located in the severe cold region. The average temperature in winter is lower than -20 °C, and the minimum temperature can reach -40 °C. The main steam temperature of the incinerator is 450 °C, the main steam pressure is 4.0 MPa, and the furnace type is counter-flow. The schematic diagram of the grate incinerator is shown in Fig. 1. After the primary air is preheated by the preheater, it is delivered into the furnace from the bottom of the grate by the primary air chambers, and there is one row of secondary air nozzles on each of the front wall and the back wall.

The incinerator's fuel is domestic waste. The ultimate and the proximate analysis of the MSW are shown in Table 1. The fuel's LHV is 6011 kJ/kg.

III. MATHEMATICAL MODEL OF THE BED COMBUSTION

The waste combustion of the moving grate is simulated with Yang's mathematical model [5]. The volume of domestic waste is reduced by 90 % and its mass by 70 % during the combustion process. In the MSW combustion, the waste bed will experience drying, pyrolysis, and solid- and gas-phase combustion. There are heat conduction, convection, radiative heat transfer, and mass transfer. In addition, the size, shape, and movement direction of the randomly stacked bed particles will change continuously. The mathematical model of waste combustion is complex, and the principal control equations for the gas and solid phases of the waste bed are presented.

Gas-phase continuity equation:

$$\frac{\partial(\phi\rho_g)}{\partial t}+\frac{\partial(\phi\rho_g V_g)}{\partial x}=S_{sg} \tag{1}$$

Gas-phase species transport equations:

$$\frac{\partial(\phi\rho_g Y_{ig})}{\partial t}+\frac{\partial(\phi\rho_g V_g Y_{ig})}{\partial x}=\frac{\partial}{\partial x}\left(D_{ig}\frac{\partial(\phi\rho_g Y_{ig})}{\partial x}\right)+S_{Y_{ig}} \tag{2}$$

Gas-phase energy equation:

$$\frac{\partial(\phi\rho_g H_g)}{\partial t}+\frac{\partial(\phi\rho_g V_g H_g)}{\partial x}=\frac{\partial}{\partial x}\left(\lambda_g\frac{\partial T_g}{\partial x}\right)+S_{a h}h_s'(T_s-T_g)+Q_h \tag{3}$$

Solid-phase continuity equation:

$$\frac{\partial((1-\phi)\rho_p)}{\partial t}+\frac{\partial((1-\phi)\rho_p V_s)}{\partial x}=-S_{sg} \tag{4}$$

Solid-phase species transport equation:

$$\frac{\partial((1-\phi)\rho_p Y_{is})}{\partial t}+\frac{\partial((1-\phi)\rho_p V_s Y_{is})}{\partial x}=-S_{Y_{is}} \tag{5}$$

Solid-phase energy equation:

$$\frac{\partial((1-\phi)\rho_p H_s)}{\partial t}+\frac{\partial((1-\phi)\rho_p V_s H_s)}{\partial x}=\frac{\partial}{\partial x}\left(\lambda_s\frac{\partial T_s}{\partial x}\right)+S_{a h}h_s'(T_g-T_s)+\frac{\partial q_r}{\partial x}+Q_{sh} \tag{6}$$

IV. NUMERICAL SIMULATION OF THE BED COMBUSTION

A. PARAMETER SETTING OF FLIC

FLIC can simulate the bed combustion of fuel, such as biomass and domestic waste. Users input the fuel's parameters in FLIC, such as the proximate analysis, the ultimate analysis, the LHV, the primary air distribution, the grate area, and the oxygen mass fraction. FLIC achieves the temperature and composition distribution of the fuel bed's gas and solid phases by solving the fuel's mass, momentum, species transport, and energy control equations. The results can be imported into Fluent as the boundary condition.

The control equations are discretized along the length and height of the fuel bed. The SIMPLE algorithm is used

TABLE I. Ultimate and proximate analysis of MSW

Ultimate analysis (as received)/%						Proximate analysis (as received)/%			
C	H	O	N	S	Cl	M	V	FC	A
15.81	2.63	8.89	0.35	0.01	0.31	52	20	7	20

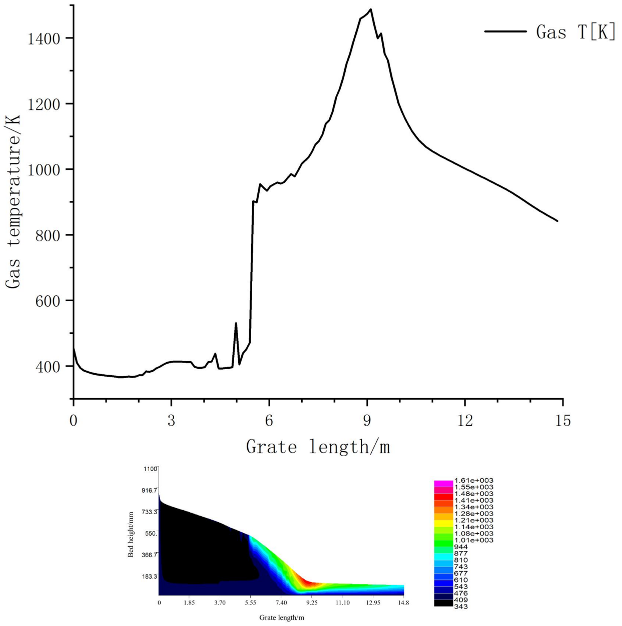


Fig. 2. Flue gas temperature analysis. (a) The temperature curve of flue gas; (b) The temperature profile of flue gas (K).

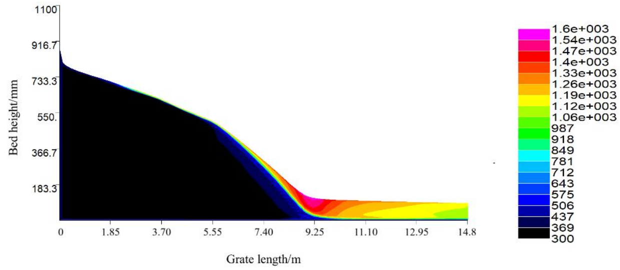


Fig. 3. The temperature profile of solid phase (K).

to solve the control equations, and the fourth-order Runge-Kutta algorithm is used to solve the radiation equations. In this paper, the volume composition of the volatile is assumed to be CmHn (26.79%), CO (73.21%), and waste fuel is ignited by the furnace radiation. The fuel particle size at the bed's inlet is categorized into five groups of 5cm×5cm×1 and 7cm×7 cm×4. The shape factor of the fuel particles is 1.50. The bulk density of the waste fuel at the bed's inlet is 482 kg/m3, the porosity is 0.63, and the initial height of the waste bed is 868mm. The primary air volume is 1229.1 Nm3/min, the excess air ratio of the primary air is 1.3, the primary air temperature is 180 °C, and the bed's moving speed is 8.47 m / h.

B. SIMULATION RESULTS

The combustion calculation results are as follows: the moisture evaporation rate is 91.65 %, the emission rate of the volatile is 100 %, the combustion rate of the fixed carbon is 54.49 %, and the total mass loss of the fuel is 78.32 %. The results show that the bed has a high degree of burnout.

Fig. 2 and Fig. 3 show the temperature distribution of the gas and solid above the grate. Because the incinerator is located in the severe cold region, the temperature of the waste incoming into the furnace is low. After the waste fuel enters the furnace through the grate, it is predominately heated by the furnace's radiation and the primary air, so the heating rate of the fuel bed is slow. From Fig. 2b, it can be seen that the fuel is in the dry stage with a low rate of change of the bed's temperature and height until 5.4m along the grate's moving direction. At 5.4m, the fuel has passed through the drying section of the grate and is approaching the middle of the grate's combustion section. After 5.4m, the volatile begins to escape and burn, the furnace temperature increases rapidly, and the evaporation rate of the bed's water accelerates. The fuel is in the pyrolysis stage, and the bed's thickness decreases rapidly due to the escape of the water and the volatile. Because the fuel pyrolysis needs to absorb heat, the gas temperature at the bed's top gradually increases. Due to the volatile's violent combustion, the grate's fuel temperature gradually increased, reaching the highest temperature of 1602K at 9m ~ 9.3m. The gas temperature at the bed's top also increases, reaching a maximum temperature of 1488K at 9.1m. After 9.1m, the volatile combustion ends, and the fuel temperature decreases. As the fuel temperature exceeds 1300K, the fixed carbon in the waste begins to burn rapidly. The ignition temperature of the fixed carbon is high, and the waste temperature decreases along the grate's moving direction. Although the primary air temperature is 180 °C, it is not enough to ensure the stable combustion of the fixed carbon. Therefore, the combustion rate of the fixed carbon at the grate's outlet is only 54.49 %, and the burnout rate of the fixed carbon is low.

Fig. 4 shows the changes in the mass fraction of the components in the waste combustion process. The change in moisture mass fraction is shown in Fig. 4(a). Because the bed is affected by the furnace's radiative heat transfer and the primary air's convective heat transfer, the water escapes from the waste fuel. It is parabolically distributed along the bed's height. Fig. 4(b) shows the change of the volatile mass fraction. Compared with Fig. 3, it can be seen that when the temperature of the waste bed reaches 533K, the volatile begins to escape and burn. Because the water and the volatile escape simultaneously, the bed's height decreases

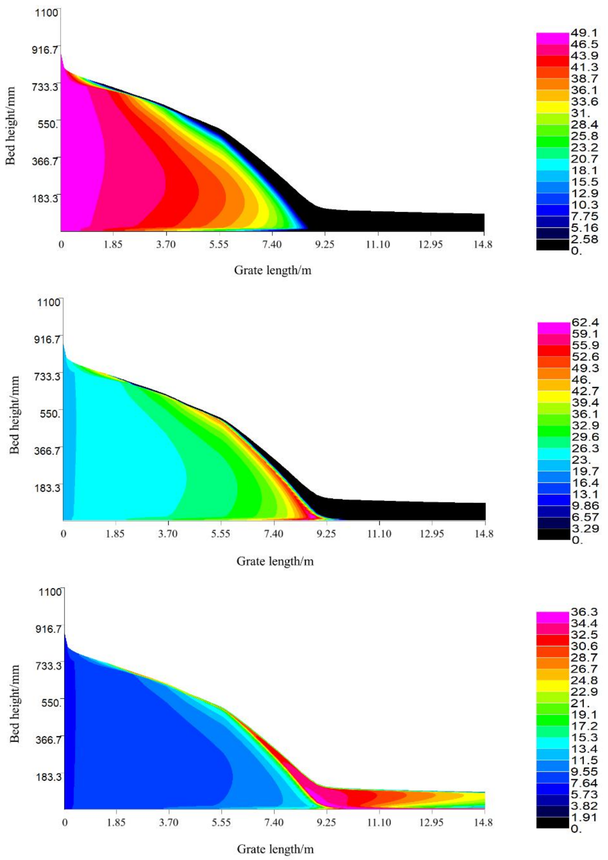


Fig. 4. The mass fraction changes of composition contents. (a) Mass fraction of the moisture; (b) Mass fraction of the volatile; (c) Mass fraction of the fixed carbon.

swiftly, and the volume of the waste fuel shrinks promptly. The mass fraction change of the fixed carbon is shown in Fig. 4(c). Due to the high ignition temperature of the fixed carbon, the change in its content is not significant until the volatile escapes and burns vigorously. Through the furnace radiation and the heat release of the waste combustion, the temperature of the waste bed exceeds the ignition temperature of the fixed carbon, and the fixed carbon begins to burn. The content of the fixed carbon changes rapidly in two stages: The first stage is the content increase of the fixed carbon from the initial 7% to 36.3% after the volatile begins to escape and burn. The second stage is that when the fixed carbon starts to burn, its content decreases from 36.3% to 20.5% at the grate's outlet.

Figs 5 and Fig. 6 show the release rates of compositions in the fuel and the changes in the mass fraction of components in the flue gas. The water is precipitated from the waste fuel from 0m to 8.8m along the grate's moving direction. From 5.4 m, the bed temperature continues to rise. When the bed temperature reaches 533K, the volatile in the fuel begins to escape. When the combustible gas in the volatile begins to burn, the oxygen mass fraction drops significantly to near 0 %, generating CO2 and H20. At about 7m, the surface temperature of the bed reaches 1015K. The fixed

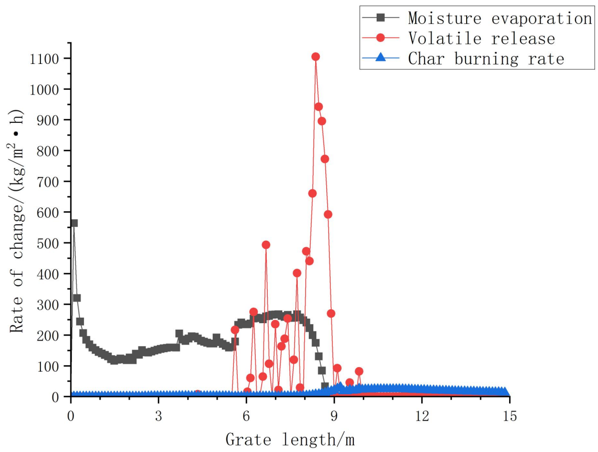


Fig. 5. The release rates of compositions.

carbon starts to burn and generate CO2. At 9.2 m, the bed reaches the highest temperature of 1602K, and the combustion rate of the bed is at its highest. At 10m, the volatile combustion ends. Since the fixed carbon begins to burn in the second half of the grate's combustion section, its combustion continues up to the grate's outlet, and the surface temperature of the bed decreases to 842K at the grate's outlet. As shown in Fig. 5, less oxygen is required in the grate's burnout section, and the mass fraction of oxygen rises to 14.5% at the grate's outlet. It can be seen from Fig.5 that there are two peaks in the volatile emission. Due to the furnace's radiative heat transfer and the primary air heating, the bed's temperature increases. The volatile escapes and the first peak appears. The heat on the bed's surface has not been completely transferred to the inside of the bed, and the release rate of the volatile gradually decreases. When the temperature inside the bed increases, the volatile precipitates and the second peak emerges. The primary components of the volatile are hypothesized to be CmHn and CO, and they show the equivalent release behavior. The fuel is subjected to the furnace's radiative heat transfer and the primary air's convective heat transfer. Its temperature ascends rapidly, and the moisture inside it precipitates quickly. Therefore, the first peak occurs. The evaporation rate of water gradually declines as heat absorption is required for evaporation. When the bed temperature increases, some of the volatile escapes and burns. It improves the moisture precipitation rate, and the second peak occurs. The third peak in the water evaporation appears when the volatile escapes rapidly and burns intensely.

V. OPERATION OPTIMIZATION ANALYSIS

The incinerator is located in the severe cold region, and the fuel's temperature is low. It is suggested that the fuel be preheated by a direct air preheater to increase the temperature of the incoming waste. The furnace's structure can be optimized with a fully adiabatic design. The heavy furnace wall structure can be adopted on the left and right sidewalls. The adiabatic insulation materials can be employed

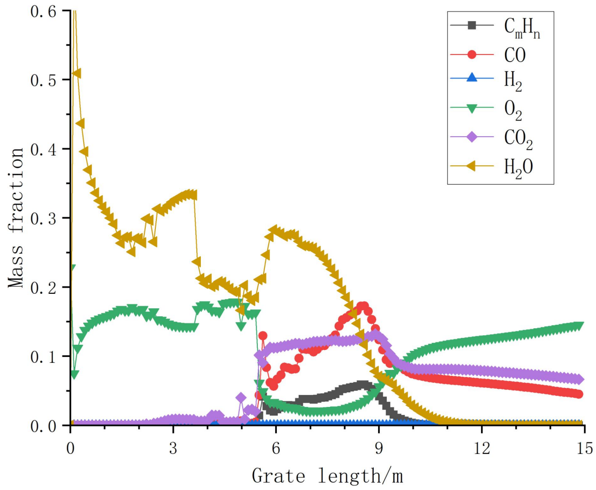


Fig. 6. The changes in mass fraction of flue gas.

on the front and rear arches to reduce the furnace's heat loss. The primary air distribution can be optimized in the practical operation to improve the burnout rate. The moisture evaporates from 0m to 5.5m, and the release amount of the volatile is low. A small amount of oxygen is required, so the primary air volume at this stage can be 10% of the total air volume. The volatile releases and burns from 5.5m to 10m, and the fixed carbon gasifies. It needs a large amount of oxygen, and the primary air volume at this stage can be above 70% of the total air volume. The fixed carbon burnout section is from 10m to the grate's outlet. The primary air volume at this stage can be 20% of the total air volume. By optimizing the primary air distribution, the burnout rate can be increased, and the heat loss caused by unreasonable air distribution can be reduced. By adjusting the angle of the front and rear arches, the furnace's heat radiation to the fuel can be enhanced, and the fuel's temperature can be increased. In order to strengthen the convective heat transfer of the primary air, its temperature can be raised to advance the fuel's ignition position. It can improve the fixed carbon combustion and waste burnout rates.

VI. CONCLUSIONS

In this paper, the numerical simulation of a waste incinerator in the severe cold region in the three northeastern provinces of China is conducted. The temperature distribution of the gas and solid phases is obtained. The variation of the fuel's compositions and the primary components of the flue gas is achieved. The results show that the combustion process of the waste bed can be divided into three stages: moisture release, volatile escaping and burning, and fixed carbon ignition and burnout. Under the severe cold operating conditions, the moisture and the volatile precipitation are slow due to the low temperature of the fuel. Because the ignition position of the fixed carbon is behind, the combustion rate of fixed carbon is low. It affects the burnout rate of the waste. According to the combustion characteristics of waste in the severe cold region, the primary air distribution can be optimized to reduce the heat loss of the incinerator and improve the combustion efficiency. The angle of the front and rear arches is suggested to adjust to enhance the furnace's radiation intensity to the fuel and increase the fuel's temperature. Because the ignition position of the fixed carbon is behind, the burnout rate of the fuel is low. The primary air temperature is suggested to be raised to advance the ignition position of the fixed carbon and improve its burnout rate. The simulation results provide a reference for the operation and structure optimization of the waste incinerators in the severe cold regions.

ACKNOWLEDGMENT

This work was financially supported by the Wuzhou University Research Foundation for Advanced Talents (Grant No. WZUQDJJ201927107).

REFERENCES

[1] X. Wang, A. Liu, H. Zhong, et al., “Characteristics of municipal solid waste in some urban agglomeration in the past five years,” Environmental Science, vol. 44, no. 11, pp. 6421–6432, 2023.
[2] Y. Wang and Y. Cao, “Analysis on garbage caloric value in MSW incineration power plant in China,” Environmental Sanitation Engineering, vol. 27, no. 5, pp. 41–44, 2019.
[3] Y. B. Yang, Y. R. Goh, R. Zakaria, et al., “Mathematical modelling of MSW incineration on a travelling bed,” Waste Management, vol. 22, no. 4, pp. 369–380, 2002.
[4] Y. B. Yang, J. Goodfellow, D. Ward, et al., “Cutting wastes from municipal solid waste incinerator plants,” Process Safety and Environmental Protection, vol. 81, no. B3, pp. 143–155, 2003.
[5] Y. B. Yang, H. Yamauchi, V. Nasserzadeh, et al., “Effects of fuel devolatilisation on the combustion of wood chips and incineration of simulated municipal solid wastes in a packed bed,” Fuel, vol. 82, no. 18, pp. 2205–2221, 2003.
[6] X. Ma, G. Liu, and Z. Yu, “Combustion optimization of municipal solid waste incinerator based on CFD,” Journal of South China University of Technology (Natural Science Edition), no. 2, pp. 101–106, 2008.
[7] Z. Qu, “Numerical simulation of waste incinerator chamber under low atmospheric pressure with gas combustion,” Environmental Sanitation Engineering, vol. 25, no. 5, pp. 84–87, 2017.
[8] Z. Zhang, H. Sun, and D. Ma, “Simulation and optimization of combustion process of the MSW incinerator in Lhasa,” Environmental Sanitation Engineering, vol. 31, no. 4, pp. 35–40, 2023.
[9] T. Lin, Y. Liao, X. Yan, et al., “Structure optimization of 350t/d waste incinerator,” Journal of South China University of Technology (Natural Science Edition), vol. 49, no. 7, pp. 116–124, 2021.
[10] X. Yang, Z. Yu, Y. He, et al., “Numerical simulation of municipal domestic waste blending with combustion of high calorific value industrial solid waste in waste incineration furnace,” Clean Coal Technology, vol. 29, no. 9, pp. 98–108, 2023.
[11] W. Zeng, Y. Wang, Q. Bu, et al., “Study of co-incineration characteristics of aged refuse and municipal solid waste,” Journal of Huazhong University of Science and Technology (Natural Science Edition), vol. 53, no. 1, pp. 107–113, 2025.