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Shiqiao Yang

Southeast University

Qingfeng Kong

Southeast University

Dewang Zeng

Southeast University

Shiliang Wu

Southeast University

Feng Gong

Southeast University

Rui Xiao (✉ ruixiao@seu.edu.cn)

Southeast University

Research

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Simulation Research on 40t/d Counter-flow Rotary Kiln Incineration System

Shiqiao Yang^{1,2}, Qingfeng Kong¹, Dewang Zeng¹, Shiliang Wu¹, Feng Gong¹, Rui Xiao^{1*}

¹Key Laboratory of Energy Thermal Conversion and Control of Ministry of Education, Southeast University, Nanjing 210096, China

² Everbright Environmental Technology Equipment (Changzhou) Co., Ltd., 213011, China

Abstract In this paper, a counter-flow rotary kiln incineration system with a processing capacity of 40 t/d of an environmental protection company in Jiangsu Province was used as the research object, and the mixed pyrolysis model and computational fluid dynamics (CFD) model of the counter-flow rotary kiln incineration system were established using Aspen plus and Fluent software. The influence of the operating temperature of the rotary kiln, the heating value of solid waste, the operating load of the rotary kiln, and the primary air volume and primary air speed on the operating effect of the rotary kiln were explored. Operating temperature, primary air volume and wind speed can all have a greater impact on the incineration performance of the counterflow rotary kiln. When the operating temperature of the counter-flow rotary kiln is greater than 800 °C, the hazardous waste heat value is not less than 1500 kcal/kg, and the primary wind speed is 1.5 m/s, the operating effect of the counter-flow rotary kiln incineration system is the best. The simulation results can provide theoretical guidance for the design and optimal operation of the counterflow rotary kiln incineration system.

Keywords solid waste, model, Aspen plus, FLUENT, simulation

1 Introduction

Since the reform and opening up, the rapid development of various industrial fields in China has led to a significant increase in social and economic standards, but at the same time, the problem of environmental pollution has also become more serious (Nanda and Berruti 2021). Global warming is becoming an increasingly serious problem as CO₂ emissions increase year on year. As a result, a global 'carbon peak and carbon neutral' goal has been proposed to improve global warming. Solid waste is one of the main pollutants juxtaposed with waste gas and liquid waste, which can cause serious harm to the atmosphere, soil and water (Visvanathan 1996). Solid waste is a major source of carbon emissions (Wang and Geng 2015), so, it is necessary to explore a reasonable and effective way of solid waste disposal, which is one of the key tasks to implement the concept of sustainable development and solve the environmental

pollution problem in the new era.

The existing solid waste treatment methods are mainly divided into two categories: resource utilization (Makarichi, et al. 2018; Singhabhandhu and Tezuka 2010) and harmless disposal (Paula Ottoboni, et al. 1998). The resource utilization of solid waste is represented by waste incineration for power generation, which not only realizes solid waste treatment but also saves energy, and meets the current development requirements of energy saving and environmental protection. However, the complexity and variety of solid waste types make the resource utilization of solid waste more difficult (Xin-gang, et al. 2016). By contrast, harmless disposal is a much simpler way of treating solid waste. Incineration and safe landfills are the two main means of harmless disposal of solid waste (Yang, et al. 2003). In terms of incineration, existing solid waste incineration technologies include

* Corresponding author. Email: ruixiao@seu.edu.cn

rotary kiln incineration, cement kiln co-incineration(Zhang, et al. 2011) and pyrolysis incineration(Qureshi, et al. 2020), of which the most widely used incineration method is rotary kiln incineration. Studies have shown that rotary kiln incineration is the most efficient way to treat solid waste(Yang, et al. 2007). Depending on whether the flow direction of solid waste and flue gas in the rotary kiln is the same, rotary kilns can be divided into two categories: down-flow rotary kilns(Eriksson, et al. 2014; Rahman, et al. 2013) and counter-flow rotary kilns(Acharya and Novak 1991; Lemieux and Pershing 1989), and most of the existing rotary kilns in China are of the down-flow type, which has the advantages of simple air and material intake and simple operation compared to counter-flow rotary kilns(Sharifah, et al. 2008). However, in actual operation, the down-flow rotary kiln suffers from uneven gas-solid mixing, easy coking and high gaseous pollutant emissions, while the counter-flow rotary kiln has more adequate gas-solid mixing and higher heat transfer efficiency in actual operation, which can better control coking and gaseous pollutant emissions(Li, et al. 2014; Pershing, et al. 1993). Counter-flow rotary kilns have been used in relatively few engineering projects at present. Therefore, the study of counter-flow rotary kiln incineration systems can help to complement this aspect and provide guidance for the future development and application of counter-flow rotary kilns.

In this paper, the mixed pyrolysis incineration process of solid waste in a counter-flow rotary kiln with a processing capacity of 40 t/d was simulated using Aspen plus software(Ismail, et al. 2020b), the temperature distribution and concentration distribution of various substances in the rotary kiln were simulated using Fluent software(Ismail, et al. 2020a; Liu and Yang 2015; Siripaiboon, et al. 2020). The factors affecting the incineration performance of counterflow rotary kilns were investigated in depth.

2 Simulation methods

2.1 Introduction to counter-flow rotary kiln incineration systems

Figure 1 shows a schematic diagram of a counter-flow rotary kiln with a horizontal inclination of 2.5° and a rotational speed of 0.2-0.5 r/min. The solid waste material enters the rotary kiln from the kiln head and moves from the kiln head to the kiln tail under the rotation of the rotary kiln, during which the solid waste undergoes drying, pyrolysis and combustion processes in turn, and the resulting ash is discharged from the kiln tail. The primary air enters the rotary kiln at the end of the kiln, where it is first preheated by the ash, and then participates in the combustion, pyrolysis and drying processes of the solid waste in turn, before forming a mixture that enters the second combustion chamber.

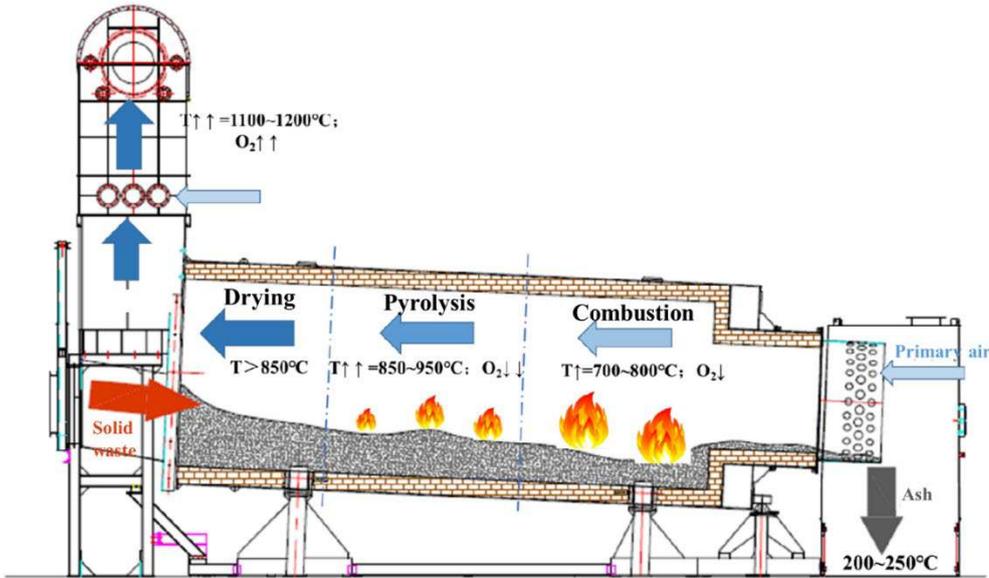


Fig.1 Schematic diagram of counterflow rotary kiln system

2.2 Aspen plus modeling

In this paper, a hybrid pyrolysis model for a counter-flow rotary kiln incineration system was simulated using Aspen plus software. The three processes of drying, pyrolysis and combustion occur sequentially in the rotary kiln, so the hybrid pyrolysis model was built by first creating a single model for each process and then connecting the single models based on the direction of material and energy flow between the models. As shown in Figure 2, the model

consists of 13 units operation modules, 20 material flow units (black solid line) and 6 energy flow units (red dashed line), which enable a counter flow reaction process between solid waste and primary air in the kiln, and the energy supply from the combustion module to the drying and pyrolysis modules through the counter flow of the energy flow units. The model contains a total of five reactors and the operating conditions for the five reactors are given in Table 1.

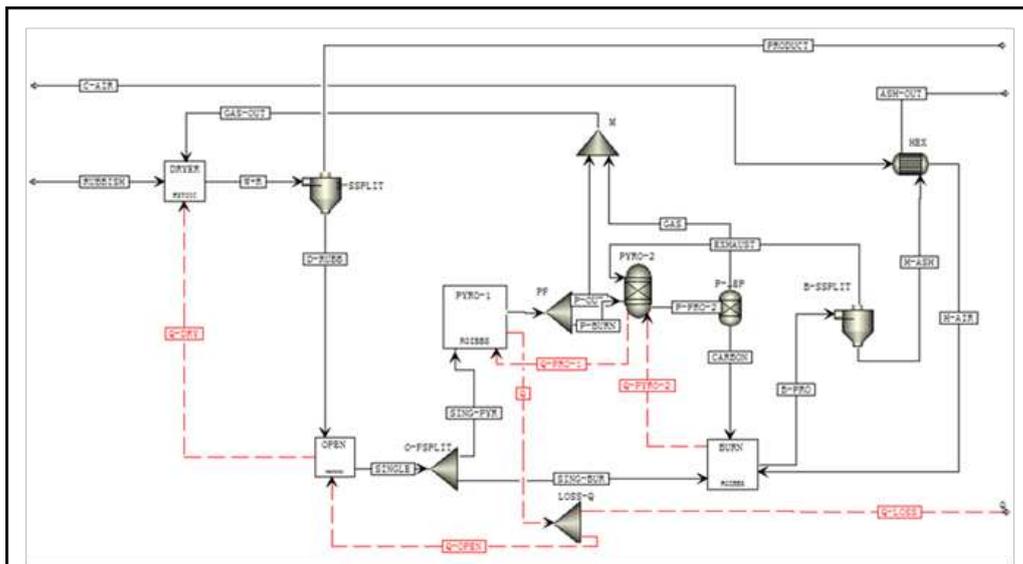


Fig.2 Hybrid pyrolysis model of countercurrent rotary kiln incineration system

Table.1 Operating conditions of each reactor

Operating conditions	Reactor modules				
	DYRER	OPEN	PYRO-1	PYRO-2	BURN

Temperature/°C	850-900	900	900	900	950
Pressure/MPa	0.101	0.11	0.101	0.101	0.101

2.3 Fluent modeling

In this paper, a CFD model of the counter-flow rotary kiln incineration system was developed using Fluent software. The physical properties of the solid waste, such as its density, were defined in the UDF user-defined mode in Fluent software, so that it existed as a "pseudo-fluid", distinct from other areas of the flow field in the kiln. By setting up the pyrolysis gasification reaction of the material in the flow field area of the kiln, the pyrolysis and combustion reactions of the material in the kiln occur on a time scale appropriate to the kiln. The pyrolysis and combustion reactions of solid waste in the kiln were adapted to the time scale of the kiln. The component transport model

was used to simulate the flow of each material component and pyrolysis gas in the kiln, resulting in the simultaneous simulation of the gas-solid two-phase flow, the pyrolysis process of solid materials and the combustion process of materials and pyrolysis gas throughout the kiln.

2.3.1 Geometric model and boundary conditions

The geometry of the counter-flow rotary kiln is shown in Figure 3, from which it can be seen that the number of inlets and outlets of the rotary kiln is four, divided into the following four categories: material inlet, primary air inlet, mixed gas outlet and slag outlet. The boundary conditions for each inlet and outlet are given in Table 2.

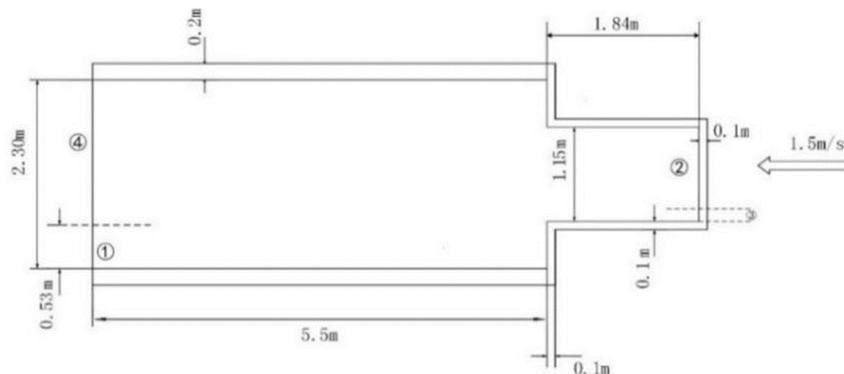


Fig.3 Schematic diagram of the geometric of the counter-flow rotary kiln

Table.2 CFD model boundary conditions

① solid waste inlet	types of boundary conditions	given inlet parameters	③ ash outlet	types of boundary conditions	given outlet pressure
	mass flow rate (kg/s)	0.463		gauge pressure (Pa)	0
temperature (K)	300				
② primary wind inlet	types of boundary conditions	given inlet parameters	④ mixture outlet	types of boundary conditions	given outlet pressure
	primary wind speed (m/s)	1.5		gauge pressure (Pa)	-50
	turbulence intensity (%)	5			
temperature (K)	300				

3.2 Mathematical-physical model

In the CFD model, the standard $k-\epsilon$ model was chosen as the turbulent flow model and a component transport model was used to simulate the chemical reaction process. Only volumetric reactions were

considered in the model, not chemical reactions on the surface, and the effect of energy diffusion and thermal diffusion on the reaction is considered.

Turbulence model:

The equation of turbulent kinetic energy k

$$\frac{\partial}{\partial t}(\rho_d k) + \nabla(\rho_d v_d k) = \nabla \left(\frac{\mu_{td}}{\sigma_k} \nabla \cdot k \right) + G_{kd} - \rho_d \varepsilon \quad (1)$$

The equation of turbulent energy dissipation rate ε

$$\frac{\partial}{\partial t}(\rho_d \varepsilon) + \nabla(\rho_d v_d \varepsilon) = \nabla \left(\frac{\mu_{td}}{\sigma_k} \nabla \cdot \varepsilon \right) + \frac{\varepsilon}{k} (C_{1e} G_{kd} - C_{2e} \rho_d \varepsilon) \quad (2)$$

Where, t is time, ρ_d is the density of mixture, v_d is the speed of mixture, μ_{td} is the turbulent viscosity of mixture, G_{kd} is the turbulent energy, C_{1e} , C_{2e} , σ_k and σ_ε are turbulence model coefficients.

Mathematical model of fluid dynamics:

The reaction equations for material and fluid dynamics in a rotary kiln generally include four equations for conservation of mass, conservation of momentum, conservation of energy and conservation of component transport.

$$\frac{\partial \rho}{\partial t} + \nabla(\rho u) = S_p \quad (3)$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u \cdot u) = -\nabla \rho + \nabla(\mu \nabla \mu) + S_N \quad (4)$$

$$\frac{\partial(\rho u)}{\partial t} + \nabla(\rho u \cdot H) = \nabla(\lambda \nabla T) + S_H \quad (5)$$

$$\frac{\partial(\rho Y_f)}{\partial t} + \nabla(\rho u \cdot Y_f) = \nabla(D \nabla(Y_f)) + S_Y + R_f \quad (6)$$

Where, ρ is the density, ρ' is the average density, u' is the instantaneous speed, p is individual gas partial pressures, μ is kinetic viscosity, H is the specific enthalpy of fluids, T is temperature, λ is thermal conductivity of fluids, Y_f is mass fraction, D is diffusion coefficient, R_f is production rate of components per unit volume, S_p , S_N , S_H and S_Y are source items.

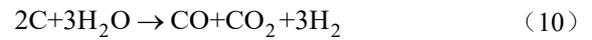
Chemical reaction model.

Seven chemical reactions were initially set up in the simulation. The chemical reactions were calculated using the Arrhenius rate model set up with the equation:

$$K = A \exp\left(-\frac{Ea}{RT}\right) \quad (7)$$

Where, K is the Arrhenius constant, A is pre-exponential factor, Ea is activation energy, R is molar gas constants.

The chemical reactions that take place in the rotary kiln are as follows:



3 Simulation results and analysis

3.1 Model validation

In the actual operation of a counter-flow rotary kiln system, the approximate temperature distribution in the rotary kiln can be obtained by means of different temperature measurement points. The average temperature in the rotary kiln is approximately 900 °C, with high temperatures in the middle of the kiln and low temperatures on the sides, with the lowest temperatures at the primary air inlet. The temperature distribution in the rotary kiln obtained from the CFD model is given in Figure 4. The graph shows that the temperature distribution in the rotary kiln is the same as the temperature distribution in the actual operation of the counter-flow rotary kiln, so the CFD model of the counter-flow rotary kiln incineration system built with Fluent software is accurate.

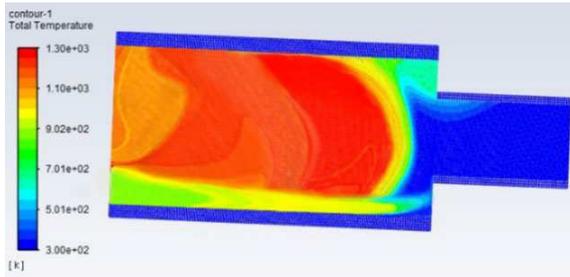


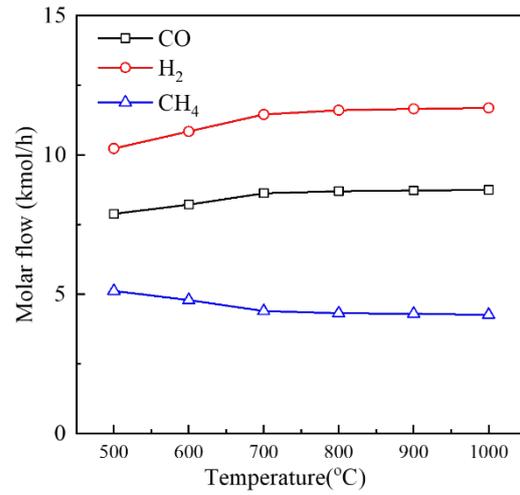
Fig.4 Temperature distribution in rotary kiln obtained by CFD model

3.2 Effect of operating temperature

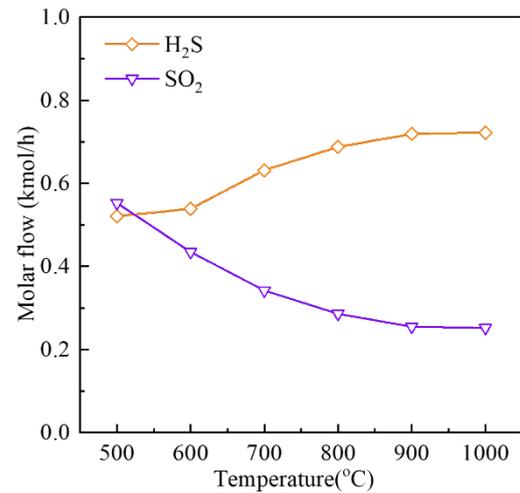
The yields of reducing gases, sulfides and nitrides obtained from mixed pyrolysis model simulations at 500 °C-900 °C are given in Figure 5. From this result, it can be seen that: with the increase of operating temperature, the contents of CO and H₂ in the mixed gas gradually increase, the contents of CH₄ gradually decrease, and the changes of the three are not significant. With the increase of operating temperature, the proportion of H₂S in gaseous sulfides increases, the proportion of H₂S in the gaseous sulfides increases and the proportion of SO₂ decreases. The proportion of HCN and NH₃ in the gaseous nitride increase and the proportion of NO decreases. SO₂ and NO are mainly produced by the combustion of fuel. The kiln tail has sufficient air and high temperatures to facilitate the production of sulfur oxides (SO_x) and Nitrogen oxides (NO_x).

However, thanks to the counter-flow characteristics of the solid waste and air, when the operating temperature of the rotary kiln incineration system increases, the N and S elements in the solid waste are more involved in the pyrolysis process prior to the combustion of the material, resulting in a reduction in the proportion of S and N elements involved in the combustion, which leads to a reduction in the proportion of SO_x and NO_x in the mixture. In addition, as can be seen in Figure 5, when the operating temperature of the counter-flow rotary kiln incineration system is above 800 °C, the yield of various reducing gases tends to stable, the content of SO_x and NO_x is lower and the emission of pollutants reaches a stable level. Therefore, the operating

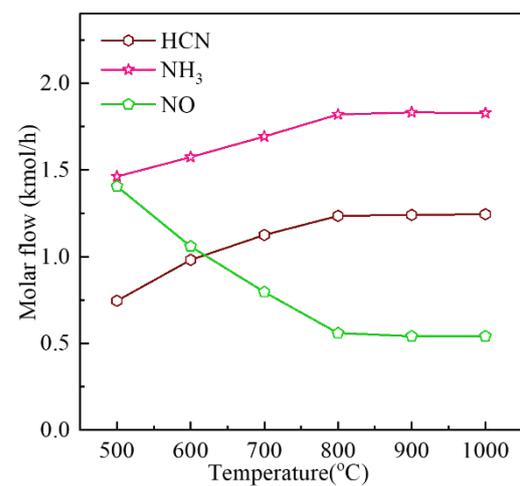
temperature should be higher than 800 °C in the actual operation of the counter-flow rotary kiln system.



(a) reducing gases



(b) sulfides



(c) nitrides

Fig.5 Pyrolysis of materials at different temperatures

3.3 Effect of solid waste calorific value

When the calorific value of the solid waste is low,

there is a risk that the counter-flow rotary kiln incineration system will not be able to meet the operating temperature of 800 °C or more, and that the high level of gaseous pollutants generated by the operation of the system will indicate that the material cannot be incinerated by the counter-flow rotary kiln incineration system. For this reason, the actual operation of the counter-flow rotary kiln incineration system was simulated using a mixed pyrolysis model with solid waste of different calorific values. Figure 6 shows the calorific values (residual heat) of the reducing gases in the gas mixture obtained from the simulated operation of the mixed pyrolysis model for solid waste with calorific values in the range of 1000 kcal/kg to 5000 kcal/kg. The simulated operating temperature is 850 °C, and the calorific values of CH₄, CO and H₂ are 8578 kcal/Nm³, 3018 kcal/Nm³ and 2576 kcal/Nm³ respectively.

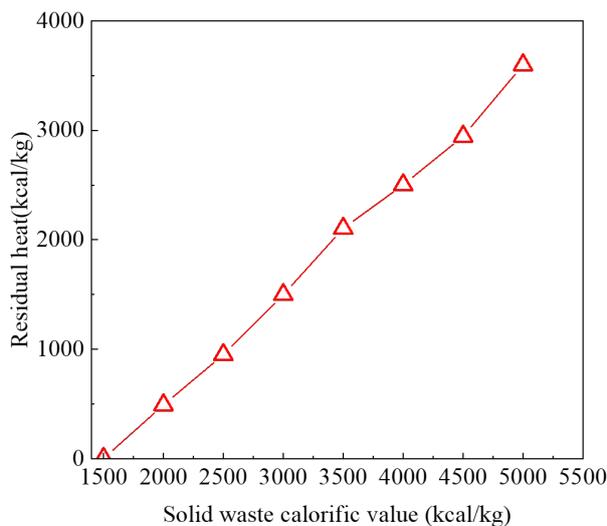


Fig.6 Residual heat in the gas mixture

As can be seen from Figure 6, when the solid waste calorific value is 1500 kcal/kg, the residual heat in the mixture entering the second combustion chamber is 3.65 kcal/kg, which indicates that the counter-flow rotary kiln incineration system can satisfy its own energy balance at an operating temperature of 850 °C, and the calorific value of 1500 kcal/kg is the critical value at this operating temperature. At a solid waste calorific value of 1000 kcal/kg, the counter-flow rotary kiln system can only

meet the energy balance at an operating temperature of 768 °C and cannot meet the required operating temperature. Furthermore, the residual heat in the mixture is approximately proportional to the calorific value of the solid waste, indicating that the counter-flow rotary kiln requires approximately the same amount of heat.

3.4 Effect of primary air volume and primary air speed

Most of the existing rotary kiln incineration systems use the negative pressure suction air supply method. In the actual operation of the system, the primary air volume and velocity are difficult to control, making the rotary kiln incineration system less stable. Therefore, the CFD model was used to adjust the primary air supply method to active air supply, and the primary air volume and speed were adjusted to investigate the effect of primary air volume and speed on the counterflow rotary kiln incineration system.

The cross-sectional area of the air inlet is constant and when the primary air velocity is adjusted to 1.2 m/s, 1.5 m/s and 2.0 m/s, the corresponding air flows are 4560 Nm³/s, 5700 Nm³/s and 7600 Nm³/s. Figures 7 and 8 give the temperature and CO concentration distributions inside the rotary kiln for the three air velocities mentioned above, respectively. As can be seen from Figure 7, the variation in air speed has a significant effect on the overall temperature distribution in the kiln. When the wind speed is 1.2 m/s, the high temperature zone in Fig.7(a) is concentrated in the combustion zone at the end of the kiln, and it can be seen from Fig.8(a) that there is still some CO generation in the combustion zone at the end of the kiln, indicating that the primary air volume is low at this time and the thermal scorch rate of solid waste is not up to the standard. As can be seen from Fig.7(b), the high temperature zone appears in the pyrolysis section at the wind speed of 1.5 m/s. In addition to the exothermic combustion of fixed carbon at the end of the kiln, some combustible volatile fractions were also

burned. High temperatures existed in both the combustion section and the gas phase zone of the pyrolysis section at the end of the kiln, and the temperature distribution in the whole rotary kiln was relatively uniform. As can be seen from Figure 8(b), the highest CO content entered the second combustion chamber at an air speed of 1.5 m/s. When the air speed was further increased to a value of 2.0 m/s, the temperature at the end of the kiln was low due to the excessive air speed and air volume. As can be seen in Figure 8(c), the high air velocity also causes a decrease in the amount of CO entering the second combustion chamber. Therefore, 1.5 m/s is the optimum air supply speed for a counter-flow rotary kiln incineration system, which corresponds to a primary air flow of 5700 Nm³/s.

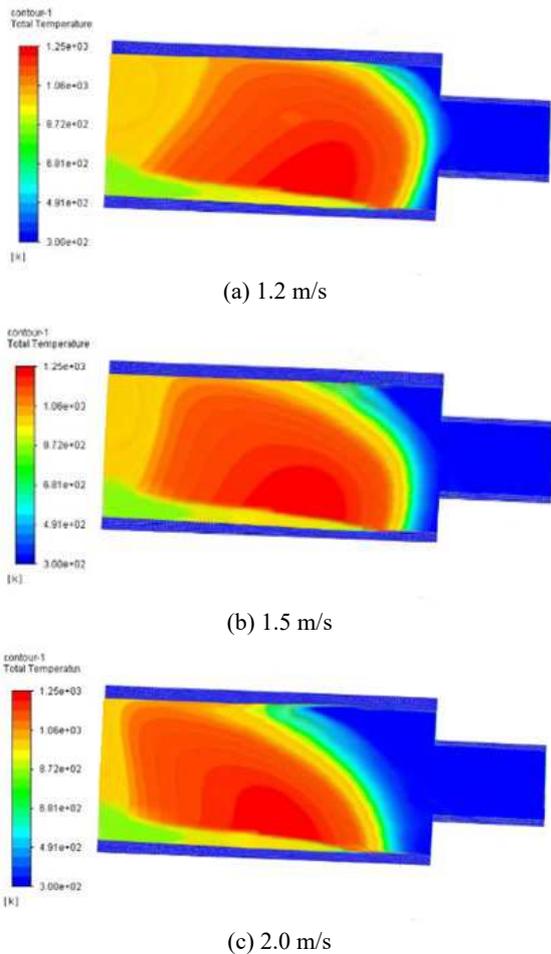


Fig.7 Temperature distribution in the kiln at different wind speeds

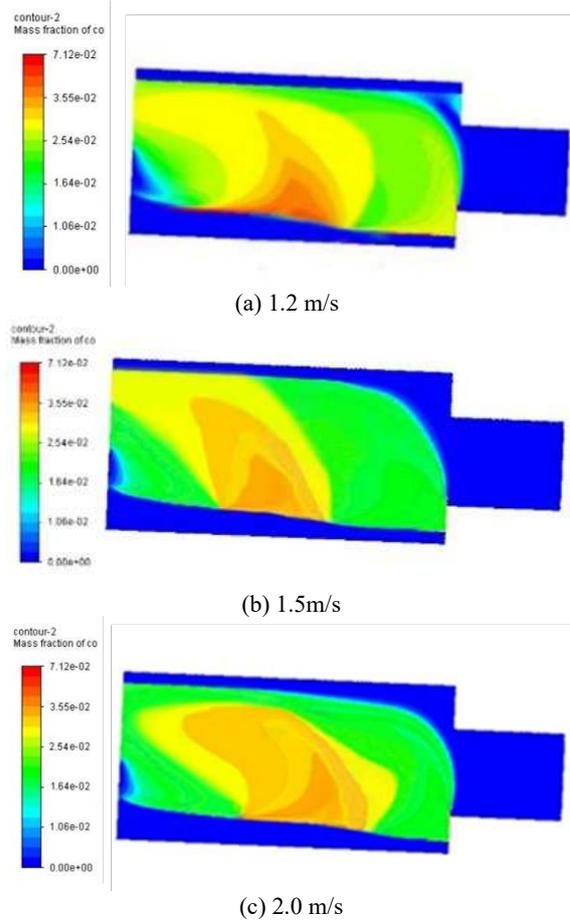


Fig.8 Distribution of CO concentration in the kiln at different wind speeds

4 Conclusion

Aspen plus software and Fluent software were used to establish a mixed pyrolysis model and CFD model of the counterflow rotary kiln incineration system respectively, and the effects of operating temperature, solid waste calorific value, primary air velocity and primary air volume on the system operation effect were investigated. The main conclusions obtained are as follows.

(1) As the operating temperature increases, the content of SO_x and NO_x gradually decreases, and when the operating temperature of the counter-flow rotary kiln incineration system is greater than 800 °C, the content of the two gaseous products tends to stable, indicating that the incineration system should meet the condition of an operating temperature greater than 800 °C.

(2) At an operating temperature of 850 °C, when the calorific value of the solid waste is below 1500

kcal/kg, the incineration system is unable to meet its own heat balance through the combustion of solid waste. With a solid waste material of 1000 kcal/kg, for example, the operating temperature of the incineration system is only 768 °C, and the treatment of solid waste is not effective. Therefore, when using this incineration system for the incineration of solid waste materials, the solid waste should be simply screened according to the different calorific values.

(3) The active air supply method helps to stabilize the operating conditions of the incineration system, but the primary air speed and the size of the primary air volume affect the actual operating effect of the incineration system. When the primary air flow and primary air speed are too small, the mixed pyrolysis of the solid waste is not complete and the thermal reduction rate of the solid waste is not up to standard. When the primary air volume and velocity are too high, the temperature field in the kiln is not uniform and the temperature at the kiln head is too high. The simulation shows that the incineration system operates best at a wind speed of 1.5 m/s, which corresponds to a primary air flow of 5700 Nm³/s.

Availability of data and materials Data and materials are available.

Competing interests No competition and interests.

Funding No funding.

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