Energy Engineering
DOI: 10.32604/EE.2020.010373
Article

Tech Science Press

Energy Conversion and Utilization System of Municipal Solid Waste

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Received: 29 February 2020; Accepted: 13 April 2020

Abstract: With the development of urbanization in China, the problem of garbage disposal has become increasingly serious. Among the existing waste treatment technologies, pyrolysis is an emerging treatment technology, which has obvious advantages in terms of reduction and secondary pollution. It has good development prospects. This article first compares the advantages and disadvantages of various existing waste treatment technologies, and proposes an organization method that combines thermogravimetric analysis, kinetic analysis, tube furnace experiments, and domestic waste pyrolysis and low-calorie heat the decomposed gases burn together. Urban garbage is one of the main pollution sources of modern urban environmental pollution in the world. Developed countries attach great importance to the study of geological disposal of solid waste. This area is a hot issue for environmental engineering workers. At present, a large number of cities have formed a serious situation of urban solid waste accumulation. The quantity of China’s urban solid waste has grown rapidly. How to deal with huge urban garbage will be a major issue related to economic development, water resources and environmental protection. This article also researches the TG-FTIR combined thermogravimetric analysis of domestic waste, the biomass pyrolysis process was observed to be similar. The second region of the weight conversion process of the energy conversion and utilization system can be described by the first-order chemical kinetic reaction of F1, and the third region can be described by the third stage of D3. Diffusion reaction to transport is described. The activation energy and pyrolysis rate of each component in the flue gas atmosphere are higher than those in the N_2 atmosphere. Finally, through research on the thermal weightlessness process and gas production process of waste, a detailed description of the recycling process of waste pyrolysis and the pyrolysis gas combustion integrated process is provided, which can act as the basis for future research on the subject.

Keywords: Domestic waste; TG-FTIR; pyrolysis; kinetic analysis; experimental device

1 Introduction

As China’s urbanization process develops, garbage disposal has emerged as a recurring problem, the output of garbage is increasing, and the various problems caused by its disposal have become increasingly difficult to resolve in the process of seeking sustainable urban development. Increasing amounts of garbage not only occupy more land, but the pollution generated also poses a huge threat to the environment and human health. In most cities in China, the phenomenon of “garbage siege” has occurred due to the lack of proper disposal facilities for garbage.

Municipal solid waste is a low-calorie value fuel comprising various organic substances. With the progress of urbanization and the change in people’s lifestyles, the production of domestic waste has continuously increased, along with its calorific value. Municipal solid waste is a misplaced and underutilized resource. If domestic waste can be converted into energy that can be effectively utilized, it can not only achieve the purpose of effective waste treatment but also ease the stress of energy in the community. The protection of a healthy natural environment is of great significance [1].

Zhang [1] introduced how the United States could improve the utilization rate of municipal solid waste through source reduction, recycling, composting and other measures. Han et al. [2] put forward the deficiencies and research directions of research on the carrying capacity of resources and environment. Dun-Dery et al. [3] put forward the perspective of circular economy theory to contribute to the healthy development of circular economy and residents.

Therefore, in the writing process of this article, through studying and researching the corresponding materials, this article starts with a variety of measures such as municipal solid waste landfill and waste energy recovery to reduce the final disposal volume of waste, and then starts from resources, environment, and ecological services. The aspects of social support and social support are analyzed comprehensively and systematically on the energy conversion and utilization system of municipal solid wastes through analysis on the solid waste resource utilization and comprehensive utilization technology.

2 Pyrolysis Kinetics Analysis and Process Heat Absorption Calculations

2.1 Pyrolysis Kinetics Analysis

Thermal analysis kinetics is a branch of chemical reaction kinetics, and it has been the main area of focus in the research on pyrolysis of domestic waste in recent decades. Pyrolysis kinetics is an important means to characterize the effect of the parameters of the pyrolysis process. By performing a kinetic analysis of the pyrolysis process, we can understand the reaction process and the mechanism in depth, determine the optimal reaction mechanism of the pyrolysis process, and calculate the pyrolysis. Kinetic parameters such as activation energy and pre-finger factors predict the difficulty of the reaction and provide important and basic data for thermochemical conversion processes. As shown in Fig. 1 [2].

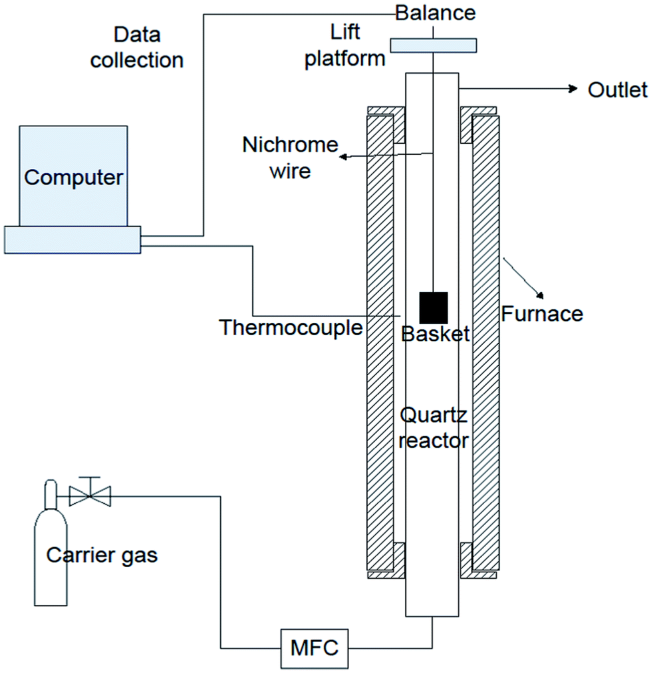

Figure 1: Pyrolysis kinetics analysis

2.1.1 Pyrolysis Kinetic Equation

The rate constant K in the kinetic equation is closely related to the temperature. The most common use is the K-T relationship proposed by Arrhenius at the end of the 19th century [3]:

$$k = A\exp(-E/RT) \tag{1}$$

In the formula, A is the pre-finger factor, min^{-1}; E is the apparent activation energy, J/mol; R is the general gas constant, 8.314 J/mol/K; T is the thermodynamic temperature, K.

Under constant temperature and homogeneous conditions, the chemical reaction kinetic equation is

$$\frac{dc}{dt} = k(T)f(c) \tag{2}$$

In the formula: c is the product concentration, t is the time, $k(T)$ is the rate constant, and $f(c)$ is the reaction mechanism function [4].

In the actual thermal analysis kinetics research process, the experimental process is usually a heterogeneous reaction system and is generally performed under non-isothermal conditions. Therefore, adjusting the chemical equations of the kinetic reaction of the homogeneous reaction at a constant temperature can obtain the reaction kinetic equation under heterogeneous conditions as follows:

$$\frac{d\alpha}{dT} = \frac{A}{\beta} f(\alpha)\exp(-E/RT) \tag{3}$$

In the formula: heating rate $\beta = dT/dt$, ℃/min; α is the conversion percentage of reaction, B%; $f(\alpha)$ is a function of the reaction mechanism.

2.1.2 Kinetic Mechanism Function

The kinetic mechanism function refers to the functional relationship between the reaction rate K of the substance and the reaction conversion rate and represents the mechanism of the reaction. Its integral form is defined as

$$G(\alpha) = \int_0^\alpha \frac{d\partial}{f(\partial)} \tag{4}$$

2.1.3 Thermal Weight Loss Process Zoning

Based on the analysis of the thermal weight loss process of the garbage components, the weight loss process is mainly divided into three phases: the water analysis phase, the volatilization phase, and the slow pyrolysis phase of coke. There are significant differences in the reaction mechanism in different pyrolysis stages, so the pyrolysis process is divided according to the development trend of the TG and DTG curves, as shown in the figure below.

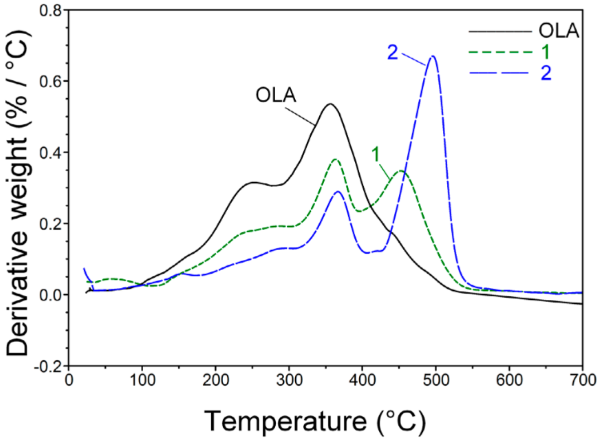

Figure 2: Schematic diagram of thermal weight loss curve division

As shown in Fig. 2, the weightlessness curve is divided into three sections according to the different stages of the thermal weightlessness process: the first section is the water analysis phase, the second section is the volatile analysis phase, and the third section is the slow pyrolysis phase of coke. Since the first zone is a drying process, only the reaction mechanisms of the second and third zones are assessed in this study. The division intervals of the second and third zones of the different waste components are shown in Tab. 1. Due to the concentration of the pyrolysis temperature of the plastic components, their kinetics were analyzed only in the second zone. The temperature interval divisions at different heating rates are shown in Tab. 2 [5].

Table 1: Division temperature of single-component waste heat loss process under different atmospheres

Type of garbage	Reaction atmosphere	Zone Ⅱ temperature interval (℃)	Zone Ⅲ temperature interval (℃)
Braised cabbage	N_2	180–400	400–990
	Smoke	180–400	400–1000
Orange Peel	N_2	170–400	400–990
	Smoke	170–400	400–1000
Wastepaper	N_2	270–410	410–1000
	Smoke	270–410	410–900
Plastic	N_2	430–530	-----
	Smoke	400–520	-----

Table 2: Zoning temperature of single-component waste heat loss process under different heating rates

Type of garbage	Heating rate (℃/min)	Zone Ⅱ temperature interval (℃)	Zone Ⅲ temperature interval (℃)
Chinese cabbage	20	180–400	400–1000
	30	190–400	400–1000
	50	190–410	410–1000
Wastepaper	20	270–410	410–900
	30	270–420	420–900
	50	270–430	430–1000
Plastic	20	400–520	-----
	30	400–530	-----
	50	410–540	-----

2.1.4 Dynamic Analysis Results

The analysis of the calculation results in Tab. 3 leads to the following conclusions:

(1) The best reaction mechanism for the two zones of Chinese cabbage in the two atmospheres is the first-order chemical kinetic reaction of F1. This stage is primarily the analysis phase of the volatilization of hemicellulose and cellulose pyrolysis. The reaction speed was fast. The phase represents the main weightless phase of the sample; the best reaction mechanism under the two atmospheres of the three zones is the diffusion reaction of D3 three-way transport. At this stage, the pyrolysis of a small amount of cellulose and the main pyrolysis of lignin yield coke. Regarding the slow pyrolysis or even burning processes, the apparent activation energies obtained in the two zone reactions under the two atmospheres are not significantly different. In the N_2 atmosphere, the value of the activation energy of the three zones is close to that of the second zone, but in the flue gas atmosphere, the activation of the three zones is caused by the presence of oxygen in the atmosphere. The activation energy can be increased, and the pyrolysis of coke requires more heat, especially when the atmosphere contains a small amount of oxygen.

(2) The best reaction mechanism of orange peel in the second zone under N_2 and smoke atmospheres is the first-order chemical kinetic reaction of F1. Since orange peel belongs to kitchen waste biomass

waste such as cabbage, it is the best in the third zone. The reaction mechanism is also the same as the three-way diffusion reaction of cabbage. At the same time, the apparent activation energy has the same size and trend, but because the orange peel contains more lignin than cabbage, the calculated apparent activation can be larger than cabbage [6].

Table 3: Analysis of reaction mechanism and pyrolysis kinetics parameters

sample	atmosphere	District Ⅱ				District III			
		Reaction mechanism	E (kJ/mol)	A (min^{-1})	r	Reaction mechanism	E (kJ/mol)	A (min^{-1})	r
Chinese cabbage	N_2	F1	41.9	1769.5	0.98	D3	46.3	1.81	0.81
	Smoke	F1	42.4	2148.3	0.98	D3	72.5	84.0	0.93
Orange peel	N_2	F1	46.0	4913.7	0.94	D3	48.37	3.61	0.83
	Smoke	F1	45.5	4492.5	0.94	D3	67.98	55.4	0.92
Wastepaper	N_2	F1	120.8	5.99	0.99	D3	56.5	9.65	0.91
	Smoke	F1	120.8	7.77	0.99	D3	80.3	61.5	0.91
plastic	N_2	F1	383.1	2.08	0.99	--	--	--	--
	Smoke	D3	427.1	3.8	0.99	--	--	--	--

(3) The best reaction mechanism of wastepaper in the second and third zones under the two atmospheres is the same as the F1 kinetic reaction mechanism and the D3 diffusion reaction mechanism. At the same time, the waste paper is a synthetic modified biomass with a very high lignin content where the energy required for pyrolysis is also high. It can be verified that its activation energy is much higher than that of the other two. The impact of paper waste on the design of the pyrolysis unit needs to consider the proportion of its lignin content.

(4) Because plastic is almost pyrolyzed in a small temperature range, only the reaction mechanism in the second zone is calculated. The reaction mechanism in the N_2 atmosphere is the F1 kinetic reaction mechanism, and the D3 diffusion reaction in the flue gas atmosphere. It is known that the plastic component is single, and the reaction rate is accelerated by the presence of oxygen in the flue gas atmosphere.

2.2 Endothermic Analysis of Biomass Waste Pyrolysis

In the experimental research in this study, biomass waste accounts for a large part of domestic waste. Because of the constant changes in the components and parameters during the pyrolysis process, calculating the heat absorption of the waste pyrolysis process has always been a problem. At present, most scholars use the formula $Q = c_p \Delta T + Q_p$ to calculate the heat absorption, where Q is the heat absorption of the process, c_p is the heat capacity of the biomass, T is the sample temperature, and Q_p is the thermal effect of the pyrolysis reaction. Two parameters, c_p and Q_p, need to be determined. However, due to the lack of current research in this area, the data used in the calculation are not uniform, and it is difficult to obtain accurate calculation results. In view of this situation, this paper uses the differential scanning thermal analyzer method to analyze the thermal effect in recent years for calculation. Because it is not necessary to determine the two parameters that change at any time, c_p and Q_p, the data obtained is more accurate. As shown in Fig. 3.

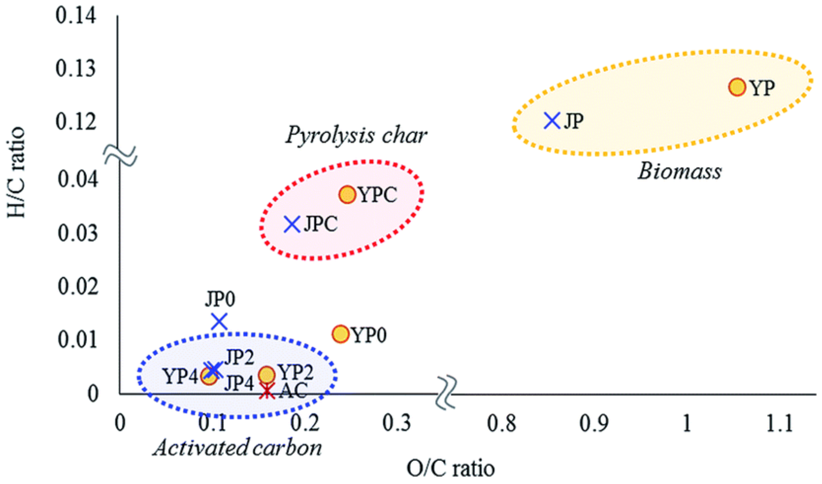

Figure 3: Endothermic analysis of biomass waste pyrolysis

2.2.1 Calculation Method of Heat Absorption

Differential scanning thermal analysis (DSC) can accurately detect the thermal effect of biomass waste during weightlessness, so it can be applied to analyze the pyrolysis process and heat absorption of the process. The thermal effect data for each stage of thermal weightlessness are clarified. Through the analysis of the data, the heat absorption of different components when they reach the pyrolysis temperature state can be calculated. The DSC curve obtained by TG-DSC analysis includes two parts: the heat required to heat the sample to the reaction temperature and the heat required to dry and react the sample. The ordinate in the DSC curve is up to the heat absorbed or emitted per g of sample per unit time. The calculation formula is as follows [7]:

$$\frac{dQ}{dt}=c_p\frac{dT}{dt}+Q_p \tag{5}$$

Among them:

Q-heat absorption of sample, kJ;

T-absolute temperature, K

T-time, Fs;

c_p -Sample heat capacity, kJ/kg/K

Q_p -Heat flow caused by reaction heat effect, kJ/kg/K

2.2.2 Calculation of Heat Absorption

Based on the analysis of the thermal weight loss process in the smoke atmosphere of the typical components of the domestic waste selected above, the thermal decomposition of plastics is mainly a continuous endothermic reaction, and the impact of the thermal weight loss of plastics and the gas production is small, so this section only analyzes and calculates the heat absorption in the pyrolysis process of the selected biomass garbage cabbage, orange peel, and waste cardboard in the smoke atmosphere.

According to the DSC curve obtained in the pyrolysis experiment, process caloric analysis was performed on three types of biomass waste products including cabbage, orange peel, and wastepaper. The DSC curves obtained from the pyrolysis experiments of cabbage, orange peel, and wastepaper are shown in Fig. 4 below [8].

From the analysis of the DSC curves of the three substances obtained in Fig. 2, it can be seen that the three components are endothermic during the pyrolysis process: the cabbage is a strong endothermic process at 200–-400℃. The thermal peak then enters a relatively stable endothermic process; the orange peel has two strong endothermic peaks at 200–-600℃, and then the endothermic energy gradually decreases. The process is the same as the two weightless peaks of the pyrolysis process.

Correspondence: The pyrolysis of wastepaper is a continuous endothermic process. There are two small peaks of reduced endothermic energy at 400℃ and nearly 800℃. The main components are lignin, a small amount of hemicellulose, and cellulose. Pyrolysis and the results of more coke and O_2 and CO_2 react at about 800℃.

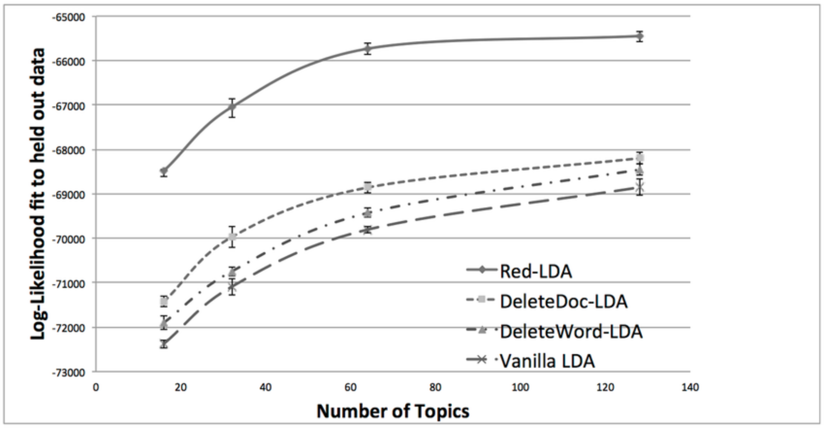

Figure 4: DSC curves of pyrolysis of cabbage, orange peel, and wastepaper in a flue gas atmosphere

In Fig. 4, the DSC curves of each sample have similarities in shape and trend, but there are some differences. In general, irregular DSC curves require special methods to accurately calculate, so integrating the DSC curve is a better method.

Through integral calculation, the thermal desorption heat of the three components can be obtained: cabbage: 1965 kJ/kg; orange peel: 2385 kJ/kg; and wastepaper: 3217 kJ/kg.

In a tube furnace pyrolysis experiment, the thermal desorption heat of biomass such as straw in an N_2 atmosphere was calculated and analyzed. It takes approximately 500 kJ/kg to increase the temperature from room temperature to 500℃. The endothermic heat obtained is the same as the endothermic heat calculated in this study. There is a large gap in the amount of analysis. The possible reasons for the analysis are twofold: on the one hand, this article is pyrolysis at room temperature to 1000℃, and on the other hand, the different pyrolysis atmospheres cause different reaction mechanisms. The reaction with coke at high temperatures requires an endothermic reaction.

3 Design of Pyrolysis and Pyrolysis Gas Combustion Cycle Equipment for Domestic Garbage

3.1 Pyrolysis Cycle Design

The domestic garbage pyrolysis and pyrolysis gas combustion cycle device in this study is an internal thermal pyrolysis process. It uses a porous media burner to organize the combustion process of low-calorific value pyrolysis gas and uses the combustion products to provide the domestic garbage pyrolysis process. In the heat and pyrolysis environment the combustion of pyrolysis products can output hot water or steam, so that there is no need to process the pyrolysis gas by cooling and decoking. It only needs to use a cyclone to remove the pyrolysis gas to enter the porous media burner. This can greatly simplify the integration of pyrolysis and combustion cycle process equipment [9].

Compared with other types of pyrolysis processes currently studied at home and abroad, in the pyrolysis and pyrolysis gas combustion cycle device in this study the combustion process of pyrolysis gas is clean, and the pollutant emission reductions will be significant reduced. No toxic substances such as dioxins will be produced, and PM2.5 emissions will be significantly reduced.

The flow chart of the domestic waste pyrolysis and low-calorific value pyrolysis gas combustion process designed according to the necessary steps of the pyrolysis and combustion process is shown in Fig. 5.

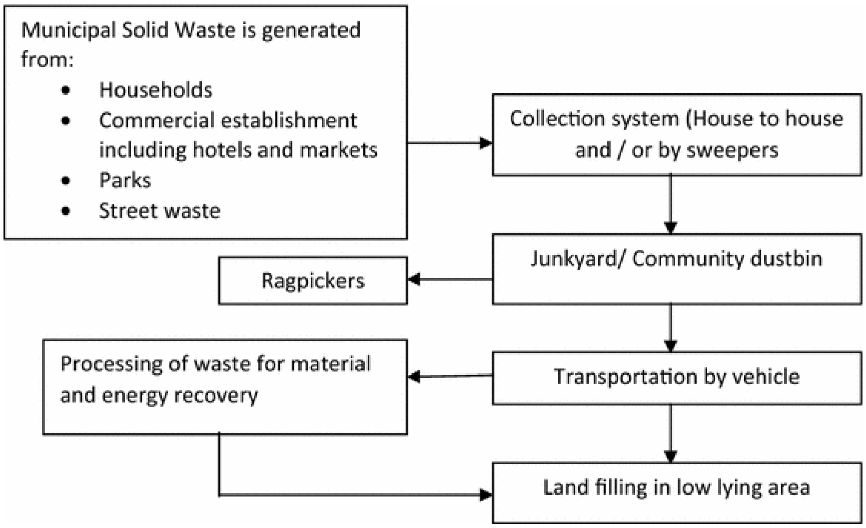

Figure 5: Flow chart of waste pyrolysis and pyrolysis gas combustion cycle process

It can be seen from Fig. 3 that the overall process is as follows. The combustion process of the low-calorific value pyrolysis gas in the combustion furnace is organized using a porous medium. The high-temperature flue gas and water system exchange heat to prepare hot water. Hot domestic waste is then discharged after denigration treatment. In the middle of the combustion furnace, a part of the medium temperature flue gas is extracted and sent to the pyrolysis furnace, so that the preheated domestic waste completes the pyrolysis process in a flue gas atmosphere, and generates low-calorie pyrolysis gas. After the pyrolysis gas is purified by the cyclone separator, it can be directly sent to the porous media burner without cooling, tar removal, and other processes. The residue produced by the pyrolysis of garbage is harmlessly treated.

The integrated circulation device mainly consists of a porous media burner, combustion furnace, flue gas suction tube, pyrolysis furnace and spiral feeding device, cyclone separator, fan, and pyrolysis gas transmission pipeline, as shown in Fig. 6 a. In Fig. 6 a, the spiral feeding device 1 is located at the head of the pyrolysis furnace 3, and the two are sealed connected by air lock 2; the cyclone dust collector 4 is located at the tail of the pyrolysis furnace 3, which is used to purify the heat degassing; the induced draft fan 5 is located behind the dust collector 4 and is used to maintain the negative pressure in the pyrolysis furnace and transport the pyrolysis gas into the porous medium burner 6; the porous medium burner 6 is located at the head of combustion furnace 7 and burns a high-temperature heat exchanger 8-2 and a low-temperature heat exchanger 8-1 are installed on the inner wall of the furnace 7. The two heat exchangers communicate with each other through an intermediate header; the medium-temperature flue gas suction pipe 9 is located in the middle of the combustion furnace 7, and one end of furnace 7 communicates with furnace 4, and the other end communicates with the first end of the pyrolysis furnace.

Domestic garbage enters the spiral feeding device from the feeding port and is pushed into the pyrolysis furnace. At the same time, an air lock is used to seal the pyrolysis furnace and the spiral feeding device to prevent air from entering the pyrolysis furnace and destroying the heat solutions to the environment.

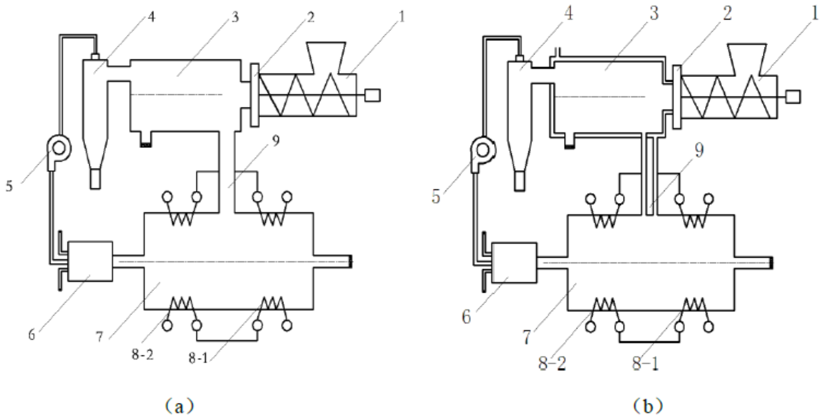

Figure 6: Schematic diagram of integrated device for pyrolysis of domestic waste and low-calorific value pyrolysis gas combustion

1. Screw feeder; 2. Air lock; 3. Pyrolysis furnace; 4. Cyclone dust collector: 5. Induced fan; 6. Porous media burner; 7. Combustion furnace; 8-1. Low-temperature heat exchanger; 8-2. High-temperature heat exchanger; 9. Medium-temperature flue gas suction pipe

Aiming at the conclusion that the proportion of combustible gas in the pyrolysis gas produced in the previous experiments is small and the calorific value is low, this paper proposes a solution that combines internal and external heat based on the design of an integrated process. In Fig. 6 b, the pyrolysis furnace and the medium-temperature flue gas extraction pipe are modified, and a heat exchange interlayer is installed outside the pyrolysis furnace so that part of the flue gas can heat the outer wall of the pyrolysis furnace through the interlayer. The medium-temperature flue gas entering the pyrolysis furnace only provides the reaction atmosphere required for pyrolysis, no longer providing all heat, and reduces the concentration of flue gas in the reaction atmosphere, which can increase the proportion of combustible gas in the pyrolysis gas.

In the main device, the pyrolysis furnace has a cylindrical structure. The spiral feed device was used to send domestic garbage into the pyrolysis furnace. Domestic garbage components were sealed in the spiral feed device and pyrolysis furnace using an air lock. Pyrolysis: The porous media burner was installed at one end of the combustion furnace and consisted of a premixing chamber and porous media. Low-calorific value pyrolysis gas is injected into the premixing chamber along the axis as a starting fuel or auxiliary. The natural fuel gas and the combustion air enter the premixing chamber tangentially. After the low-calorific value gas, natural gas, and air are evenly mixed in the premixing chamber they enter the porous medium for combustion. The combustion furnace is cylindrical with spiral tubes lining the inner wall. The spiral tube is divided into two sections, low temperature and high temperature. Through the intermediate header, water flows in the spiral tube, and its flow direction is opposite to the flow direction of the flue gas. The middle section of the combustion furnace was provided with a smoke extraction pipe perpendicular to the central axis. The other end of the gas suction pipe was connected to the pyrolysis furnace, and the connection position was near the garbage inlet of the pyrolysis furnace.

4 Conclusions

Based on the analysis of the current waste treatment industry and related research at home and abroad, this paper proposes a new waste treatment method that organizes the pyrolysis of domestic waste in a flue gas atmosphere and uses the flue gas generated by the combustion of pyrolysis gas to provide heat for pyrolysis. The key issues involved in this method were explored through thermogravimetric-Fourier infrared spectroscopy, kinetic analysis, tube furnace experiments, and gas chromatography analysis. Process design of pyrolysis cycle unit. Based on previous research on the mechanism of weight loss and gas generation during pyrolysis of waste, the overall process prediction and description of the integrated cycle device for waste pyrolysis and pyrolysis gas combustion were drawn, and the cycle flow diagram and schematic diagram of the device were drawn. The research carried out later in this topic provides a reference theoretical basis.

Funding Statement: The authors received no specific funding for this study.

Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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