

Article

Research on the Resource Treatment and Comprehensive Utilization of Carbon Containing Wastes Using Pyrolysis–Gasification Two-Stage Recycling

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Abstract: Carbon containing waste has a certain calorific value and utilization value due to the presence of carbon elements. However, the current treatment methods are mostly traditional landfill disposal, incineration, or expensive physical and chemical reaction methods, which clearly do not comply with the rules of the current clean and resource-saving society. In this paper, a new technology and system for carbon containing wastes is proposed, which comprehensively treats and recycles carbon containing wastes, including solid waste, wastewater, waste gas, etc., using pyrolysis–gasification two-stage-cycle technology. The calculation results indicate that the technical scheme proposed in this article is feasible and can achieve the recycling of intermediate and final products, the efficient and clean utilization of carbon containing waste, and the graded utilization of energy. The clean utilization rate of carbon containing waste can be effectively improved, the energy consumption and cost of separate treatments can be reduced, and zero waste emissions can be completely achieved by the comprehensive pyrolysis–gasification two-stage-cycle treatment and resource utilization technology, which is one of the preferred solutions for future resource-saving societies.

Keywords: carbon containing waste; pyrolysis–gasification two-stage cycle; zero emission; graded utilization of energy; resource treatment; comprehensive utilization



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1. Introduction

There is a consensus in the world today on the necessity and importance of using new technologies to extract liquefied chemicals and fuels from waste and low-quality energy sources. Carbon containing waste refers to various solid wastes, hazardous wastes, wastewater, waste gas, and other materials containing carbon elements. Due to the presence of carbon elements, they have a certain calorific value and utilization value. At present, solid carbon wastes, such as garbage, crop residues, sludge from sewage treatment plants, and oily sludge from petrochemical enterprises, are mostly treated using traditional landfill disposal or incineration or are simply transported and stacked outside. This not only occupies a large amount of land resources but also causes varying degrees of pollution in the soil, water, and atmosphere [1–3]. Carbon containing liquid waste, such as various types of wastewater and waste liquids containing carbon elements generated and discharged in industrial and production processes, is currently mainly treated through physical adsorption and chemical reaction methods [4]. The use of these advanced wastewater treatment devices produces good results and can achieve standard discharge, accompanied by high costs. These methods, while achieving clean emissions, require high energy consumption, which is no longer competitive and is also a major waste of water resources. In addition,

carbon containing gas wastes, such as industrial exhaust gas, have large volumes and a wide variety of types. The treatment method is similar to that of wastewater, but there is also the problem of its high cost [5,6]. In summary, how to effectively, cleanly, and economically dispose of and efficiently utilize gas, solid, and liquid carbon wastes is an urgent problem and challenge that needs to be solved for China's economic and social development.

Both the US Department of Energy's "21st Century Energy Outlook" and Japan's "21st Century Coal Technology Strategy" reports regard low-temperature rapid pyrolysis technology for producing gas, fuel, and high-value chemicals as important research projects [7]. Pyrolysis has the advantages of diversified resource utilization of products and a reduction in dioxin emissions, making it the increasingly preferred technology for solid waste treatment [8]. However, most of the large amount of semi-coke produced by pyrolysis is not suitable as raw material and can only be used for combustion in order to improve utilization efficiency. However, the direct combustion of semi-coke still faces problems such as high ash content, high hardness, and a low carbon conversion rate. Therefore, the utilization of semi-coke has become a key issue in pyrolysis technology. Gasification can generate high-performance gas-coupled power generation and is considered the main application technology for the future [3,9]. However, if carbon containing waste is directly gasified, it will lead to dry distillation products such as tar and phenol, which cannot be fully gasified, which not only affects the gasification efficiency but also causes equipment failures and secondary pollution.

Therefore, this article proposes a new technology and system for the resource utilization of carbon containing waste. From the perspective of environmental protection and economic development, the clean utilization rate of carbon containing waste is effectively improved through the pyrolysis–gasification two-stage-cycle treatment, and zero waste discharge is fully achieved. At the same time, the energy consumption and cost of treatment can be reduced, achieving efficient cleaning and the graded energy utilization of carbon containing waste.

2. System Introduction

This article proposes a comprehensive treatment and resource utilization technology and system for carbon containing wastes, which include solid waste, wastewater, and exhaust gas. The carbon containing waste is first pyrolyzed and then gasified, which is called the comprehensive two-stage-cycle treatment technological scheme, and the energy consumption and cost of separate treatments will be reduced. The intermediate and final products are recycled to reduce energy consumption and ultimately achieve the reduction in, resource utilization of, and harmless disposal of carbon containing waste. The technical principle and system flowchart are shown in Figure 1. The numbers in the figure represent the components defined below the figure.

The system mainly includes seven main components, including a self-heating pyrolysis furnace (1), gasifier (2), temporary storage silo for semi-coke (3), slag-cooling device (4), raw gas treatment system (5), syngas pretreatment system (6), and mixed-gas treatment system (7). The terms of each component are explained first in order to better understand the overall system workflow:

The self-heating pyrolysis furnace (1) is a pyrolysis furnace, with the temperature controlled between 773 and 873 K at atmospheric pressure.

The gasifier (2) is a high-temperature pressurized gasifier, with the temperature controlled within 1773~1873 K and a pressure of 0.2~2 MPa.

The temporary storage silo for semi-coke (3) is a container for the temporary storage of the semi-coke produced by pyrolysis and comprises a lower connecting pipe (301) and a pressure valve (302).

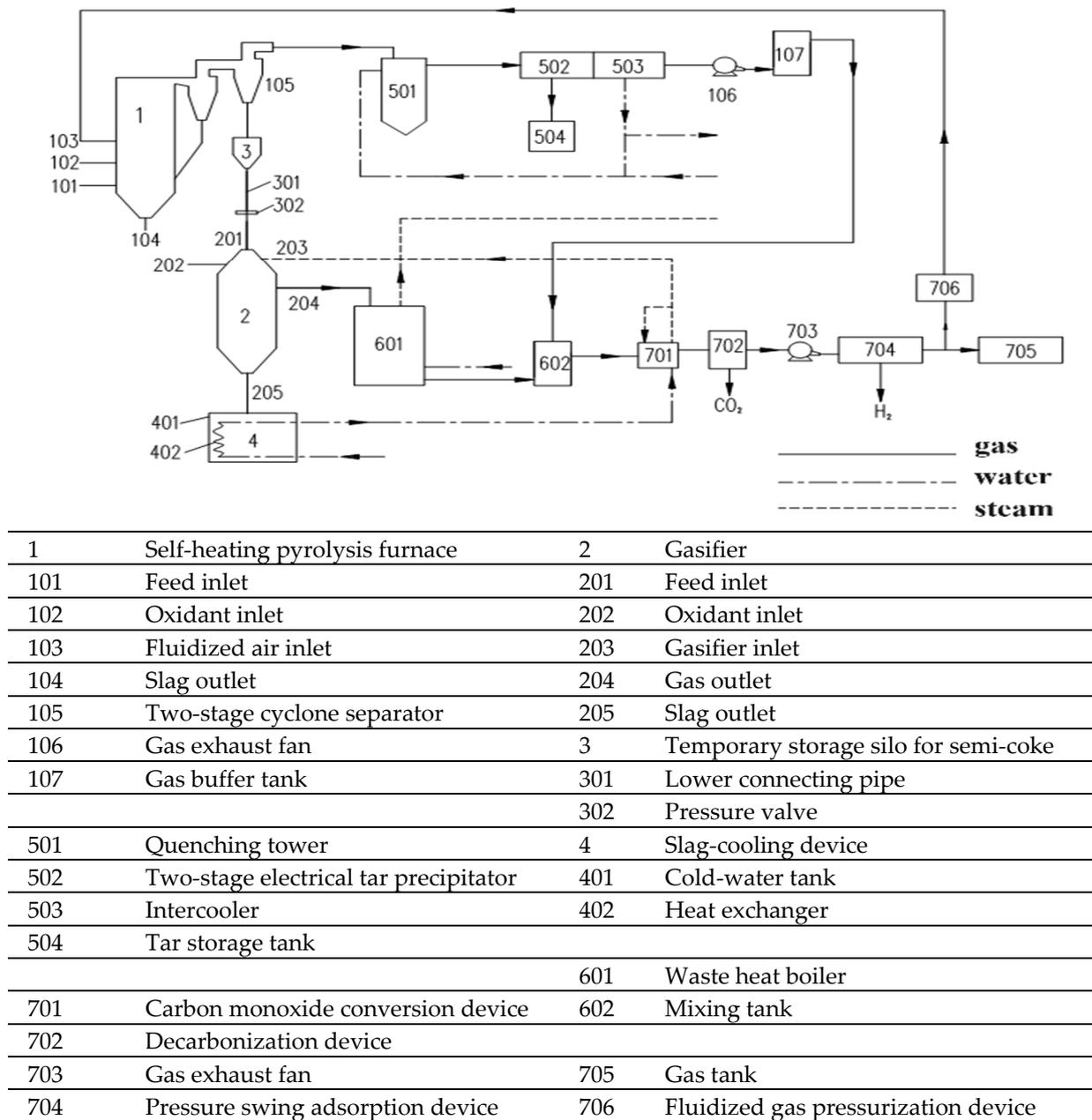


Figure 1. Technical principle and system flowchart.

The slag-cooling device (4) is a container for cooling and recovering the waste heat of the liquid ash produced in the gasifier and includes a cold-water tank (401) and a heat exchanger (402).

The raw gas treatment system (5) comprises a quenching tower (501), a two-stage electrical tar precipitator (502), an intercooler (503), and a tar storage tank (504). The quenching tower, intercooler, and two-stage electrical tar precipitator are all used to collect tar from the pyrolysis gas.

The syngas pretreatment system (6) comprises a waste heat boiler (601) and a mixing tank (602) and is used to cool down the high-temperature syngas, absorbing the heat of the syngas to produce steam for self-use.

The mixed-gas treatment system (7) comprises a sequentially connected carbon monoxide conversion device (701), decarbonization device (702), gas exhaust fan (703), pressure swing adsorption device (704), gas tank (705), and fluidized gas pressurization device (706).

The system workflow is as follows:

- a. The carbon containing waste first enters the pyrolysis furnace, and part of the carbon containing waste burns and releases heat under oxygen conditions, providing heat for the pyrolysis process. The remaining carbon containing waste undergoes pyrolysis under anaerobic conditions, and the gas produced by pyrolysis passes through a two-stage cyclone separator to obtain pyrolysis gas and semi-coke (a good high-calorific-value smokeless fuel, mainly used as industrial or civil fuel).
- b. The pyrolysis gas is purified in the raw gas treatment system, which includes the following steps: The pyrolysis gas (raw gas) first enters the quenching tower, is cooled by sprayed water, and then passes through the first electrical tar precipitator, intercooler, and second electrical tar precipitator along with water vapor. Then, the tar and water in the raw gas are separated, and the tar is sent to the tar storage tank for storage, while liquid water is recycled as cooling water for the quenching tower to obtain pure gas, which can be stored for backup or sale.
- c. Next, in the gasifier, the semi-coke generated by pyrolysis is subjected to cracking gasification in the furnace under the action of gasification agents (oxygen and saturated steam), and then the generated syngas is sent to the pretreatment system, and the liquid ash is discharged into the slag-cooling device through the slag outlet at the bottom of the furnace.
- d. The process that occurs in the syngas pretreatment system is as follows: The heat released by high-temperature syngas heats the cooling water in the waste heat boiler to produce saturated steam for heating or power generation. The cooled syngas is mixed with the clean gas from the gas buffer tank in the mixing tank to form a homogeneous mixture, which is then sent to the mixed-gas treatment system.
- e. The process that occurs in the mixed-gas treatment system is as follows: The mixed gas first enters the carbon monoxide conversion device, and the carbon monoxide in the mixed gas reacts with water to generate hydrogen and carbon dioxide. The mixed gas transformed by carbon monoxide enters the decarbonization device to separate the carbon dioxide from the mixed gas and send it out, which can be stored or used to produce dry ice. The remaining mixed gas enters the pressure swing adsorption device through the gas exhaust fan to extract hydrogen, which can be sent to the tar hydrogenation device to produce light fuel oil products. The remaining mixed gas after extracting hydrogen is sent to the gas tank for storage or sale.
- f. A portion of the gas is extracted and sent to the pyrolysis furnace through a fluidized gas pressurization device, which is used as the fluidized gas for the pyrolysis furnace to ensure the fluidization of the bed material.
- g. The waste heat of the high-temperature liquid ash is absorbed by the circulating cooling water, and this part of the circulating cooling water is just sent to the carbon monoxide conversion device to be used as the water required for the CO conversion reaction, and the excess water is heated to form saturated steam by the heat released by the carbon monoxide conversion reaction and sent to the gasifier as a gasification agent.

3. Materials and Methods

Normally, carbon containing waste refers to various solid wastes, wastewater, and exhaust gas, which contain carbon elements. Solid waste refers to the waste products generated or left behind in the production process, mainly including solid particles, garbage, slag, sludge, waste products, broken appliances, defective products, deteriorated raw materials or finished products, etc. Wastewater refers to the wastewater and waste liquid generated in industrial production, mainly including production wastewater, production sewage and cooling water. Exhaust gas refers to useless or harmful gases generated in industrial production, mainly including carbon dioxide, carbon disulfide, hydrogen sulfide, fluoride, nitrogen oxides, chlorine, hydrogen chloride, carbon monoxide, sulfuric acid (fog), lead mercury, beryllide, soot, and production dust. The system proposed in this article is

suitable for all kinds of carbon containing wastes generated in industrial production and life, including the above-mentioned solid wastes, wastewater, and exhaust gas.

In this study, two types of carbon containing wastes were selected for calculation: sample 1 from an industrial paper factory and sample 2 from a municipal wastewater plant. Sample 1 has a higher calorific value that is comparable to that of coal. The calorific value of sample 2 is low, only a little higher than the lowest limit of the calorific value of 4180 KJ/kg for household waste entering the furnace. The industrial analysis of the samples was carried out by an industrial analysis method, which is a commonly used and simple chemical analysis test method. Industrial analysis can determine the moisture, ash, and volatile contents of waste with an automatic industrial analyzer and determine the fixed carbon and calorific value of waste through a combustion test, which is similar to the industrial analysis and determination method for coal. Industrial analysis can evaluate the quality of raw materials and products so as to use raw materials and fuels economically and rationally. The industrial analysis of the samples is shown in Table 1.

Table 1. Table of industrial analysis of the samples.

Industrial Analysis	Sample 1 Value	Industrial Analysis	Sample 2 Value
FCad	49.5%	FCad	8.1%
Vad	28.9%	Vad	37.6%
Mad	11.6%	Mad	53.1%
Aad	10.0%	Aad	1.2%
Qnet.ar	24,396 KJ/kg	Qnet.ar	6558 KJ/kg
Gray-King tar yield	8.5%	Gray-King tar yield	8.5%

Note: FCad means the content of fixed carbon, Vad means volatile content, Mad means moisture content, Aad means ash content, and Qnet.ar means a low calorific value. The percentages in the table refer to the mass percentages.

The temperature inside the self-heating pyrolysis furnace is 873 K, which makes it low-temperature pyrolysis. Low-quality energy sources with higher volatile content, such as waste, can be used in low-temperature pyrolysis, and during the pyrolysis process, tar and gas can be recovered. By utilizing the natural advantage of hydrogen in the molecular structure of waste, the hydrogen enriched in the waste can be extracted for high-quality liquid and gaseous energy or chemical raw materials through pyrolysis. Therefore, low-temperature pyrolysis can enable the rational and efficient utilization of low-calorific-value and low-quality waste, and it is currently the most economical, effective, and rational utilization method of waste [10]. The pyrolysis model comprehensively considers heat transfer, diffusion mass transfer, pyrolysis kinetics and secondary cracking reaction [11]. In establishing a comprehensive pyrolysis model, heat transfer factors are first considered; that is, the entire particle is treated in a nonisothermal pyrolysis mode. The components of pyrolysis products are tar and gaseous volatiles, and a second-order-reaction single-equation model is used for the formation kinetics of the primary product of pyrolysis:

$$\frac{dV_i}{dt} = k_{0i} \exp\left(-\frac{E_i}{kT}\right) (V_{i\infty} - V_i)^2 \quad (1)$$

In the formula, $i = 1$ corresponds to the tar component; $i = 2$ corresponds to the gaseous pyrolysis product; k_0 is the pre-exponential factor, 10^{13} s^{-1} ; E represents active energy, kJ/mol; k represents the gas constant, $8.314 \text{ J/mol}\cdot\text{K}$; and T is the temperature, K.

The mass and energy conservation equations of tar and gaseous pyrolysis products in a two-component pyrolysis system are considered, and the basic equations of the pyrolysis product precipitation model are constituted, which comprehensively considers heat transfer, diffusion and mass transfer, pyrolysis kinetics, and secondary cracking reactions. With the initial conditions given, the total amount of pyrolysis product precipitation can be calculated using MATLAB calculation software (MATLAB 7.8.0 R2009a) [12].

Based on the above model and formula, 1000 kg/h carbon containing waste (sample 1) with a calorific value of 24,396 kJ/kg is pyrolyzed in an 873 K pyrolysis furnace. According to the heat and mass transfer equation, 287 Nm³/h of oxygen at 293 K and 515 Nm³/h of fluidized gas at 313 K are sent into the pyrolysis furnace to maintain a fluidized state inside the furnace. The heat required for the pyrolysis process is provided by the incoming materials themselves. According to calculations, a total of 154 kg/h of carbon containing waste is required to burn and release heat under oxygen conditions, providing a source of heat for the pyrolysis process; most of the remaining carbon containing waste (846 kg/h) undergoes low-temperature pyrolysis at 873 K under anaerobic conditions, generating pyrolysis gas (containing water and tar) and semi-coke. Previous studies have shown that before 873 K, CO₂ and CO reach the final yield of volatile matter, and NH₃ and H₂S are also close to the final yield, indicating that the main pyrolysis process of carbon containing materials is basically completed at 873 K [13]. The calculation formulas for the main pyrolysis products at 873 K are as follows:

$$CH_4 = (-0.088 \ln C\%) \times 100 \times 22.4/1000 \times 0.55 \quad (2)$$

$$H_2 = (H \times V_{ad} / (V_{ad} + FC_{ad}) - NH_3 \times 1000/22.4 \times 3 - H_2 S \times 1000/22.4 \times 2 - C_m H_n \times 1000/22.4 \times 4) / 2 \times 22.4/1000 + H_2 O \times (1 - \delta) / \delta \quad (3)$$

$$CO = O \times 0.33 \times 22.4/1000 + H_2 O \times (1 - \delta) / \delta \quad (4)$$

$$H_2 = M_{ad} / 18 \times 22.4 \times ((273.15 + 100)) / 273.15 \times \delta \quad (5)$$

In the formulas, C% represents the molar concentration percentage of the carbon element; H and O represent the mass molar concentrations of hydrogen and oxygen elements, respectively; and δ represents the proportion of the gasification reaction.

It is worth noting that (1) the raw materials of carbon containing waste only need to be physically shredded and ground to meet the requirement for the feed particle size for the pyrolysis furnace, and there is no additional pretreatment required for the raw materials. Due to the high temperature of the system, there is no special requirement for the phase state of the raw materials. The system has a wide range of applicability and convenience. (2) The system was used identically in the pyrolysis–gasification two-stage-cycle treatment of all three sample types: solid waste, wastewater, and exhaust gas. Because of the high-temperature pressurized gasifier, with the temperature controlled within 1773~1873 K and a pressure of 0.2~2 MPa, all three types of waste, solid waste, wastewater, and exhaust gas, can be completely consumed in the pyrolysis–gasification two-stage-cycle treatment. Therefore, there is no need to consider the phase types of the samples; they can be processed individually, in pairs, or as a mixture of the three. Typically, solid waste, wastewater, and exhaust gas are mixed together in the treatment system and do not need to be separated, which can save the cost of separate treatments. (3) The gasification process is indeed a very complex process, and many process parameters, such as temperature, flow rate, biomass concentration, and time, can affect the gasification process. In this analysis, these parameters were optimized on the basis of theoretical and engineering empirical values, as well as MATLAB model calculations. (4) The waste treatment temperature in this paper is much higher than 1373 K, and the process flow of quenching tower water spray cooling is used to avoid the generation of dioxins as much as possible in the process [14]. In the tail gas treatment system, the type and composition of the waste are evaluated, and the dioxin measurement results are used to determine whether activated carbon adsorption is required.

4. Results and Discussion

The key to the comprehensive treatment and resource utilization technology and system for carbon containing waste proposed in this article is the system balance calculation, achieving the source and destination of materials, intermediate products, and production materials, as well as the balance of heat and material income and expenditure, thus demonstrating the feasibility of the system balance and the economy of energy conservation and water conservation. The calculation results are shown in Table 2.

Table 2. Production of pyrolysis gas products.

Sample 1 Composition	Yield, Nm ³ /h, 873 K Atmospheric Pressure	Sample 2 Composition	Yield, Nm ³ /h, 873 K Atmospheric Pressure
CH ₄	91.7	CH ₄	2.2
C _m H _n	12.2	C _m H _n	3.2
H ₂	145.2	H ₂	1.2
CO	56.6	CO	12.5
CO ₂	37.5	CO ₂	40.3
H ₂ O	177	H ₂ O	278.5
NH ₃	5.2	NH ₃	/
H ₂ S	1.3	H ₂ S	/
Tar	24.5	Tar	8.5
Total (containing water and tar)	551.2	Total (containing water and tar)	346.4
Semi-coke	595 kg/h	Semi-coke	340 kg/h

Note: C_mH_n stands for carbohydrate, $m \geq 2$, $n = 2m - 2$, $n = 2m$, $n = 2m + 2$.

The volumes of the gases in all tables in this article were calculated using the ideal gas equation of state by measuring the temperature and pressure of the gas. And the volumes of the gas were quantitatively determined and compared with mass flow meters. The types of gases in all tables in this article were determined by empirical and theoretical predictions of the gas composition, which were validated using a gas analyzer (corresponding gas sensor) to determine the composition of the gas mixture.

The pyrolysis products pass through the primary and secondary cyclone separators to generate pyrolysis gas (551 Nm³/h, containing water and tar, 873 K) and semi-coke (595 kg/h, 873 K). The pyrolysis gas carries the fluidized gas into the gas treatment system for purification. The fluidized gas (515 Nm³/h, mainly composed of CH₄, 873 K) in the pyrolysis furnace is extracted from the ultimate gas cabinet to ensure the fluidization of the bed material. The process is as follows: The gas first enters the quenching tower and exchanges heat with the sprayed cold-water (294 kg/h, 293 K), which results in a 1066 Nm³/h mixed gas (containing water and tar, 423 K). Then, the gas sequentially enters the first-stage electric tar catcher, intercooler, and second-stage electric tar catcher to capture 85 kg/h tar and 383 kg/h water (all at 313 K). Finally, 929 Nm³/h (313 K) of pure pyrolysis gas is obtained and sent to the gas buffer tank for storage through an exhaust fan.

Semi-coke (595 kg/h, 873 K) is sent to the top of the gasifier through the temporary storage silo for semi-coke. It is carried by oxygen (259 Nm³/h, 293 K) and saturated steam (394 kg/h, 393 K) and enters the gasifier (1873 K, 0.3 MPa) for cracking gasification. The generated syngas (1457 Nm³/h, 1373 K) is sent to the waste heat boiler, and the remaining high-temperature liquid ash (100 kg/h, 1773 K) is discharged through the outlet and sent to the slag cooling device.

The high-temperature syngas (1457 Nm³/h, 1373 K) exchanges heat with the cooling water (352 kg/h, 293 K, 4 MPa) in the waste heat boiler, heating the cooling water to form saturated steam (352 kg/h, 521 K, 3.82 MPa), which can be used for heating or power generation. The cooled syngas (1457 Nm³/h, 840 K) and pyrolysis gas (929 Nm³/h, 313 K) are mixed in a mixing tank to form a homogeneous mixture (2386 Nm³/h, 643 K). The composition is shown in Figure 2.

Usually, the carbon content of carbon containing waste determines the amount of CO and CH₄ generated after pyrolysis and gasification. The higher the carbon content, the higher the content of these two gases, and the proportion of these two gases varies depending on different experimental conditions. It can be seen in Figure 2 that sample 1, with a high carbon content and a low calorific value of 24,396 kJ/kg, undergoes low-temperature pyrolysis and high-temperature and high-pressure gasification, resulting in a higher proportion of CO in the fuel gas composition than CH₄. For sample 2, with a lower carbon content and a low calorific value of 6558 kJ/kg, the situation is exactly the opposite: CH₄ accounts for a higher proportion than CO. This indicates that the ratio

of CH₄ to CO in the pyrolysis and gasification products of carbon containing waste is determined by the carbon content, and the carbon content in the raw materials directly and mainly determines the amount of CO generated, with little impact on the amount of CH₄ generated. In addition, sample 1, with a higher carbon content and a low calorific value of 24,396 kJ/kg, generates more H₂ than sample 2, with a lower carbon content and a low calorific value of 6558 kJ/kg, even exceeding it two-fold, indicating that the contribution of hydrogen content to the low calorific value of waste samples is also significant, second only to the carbon content.

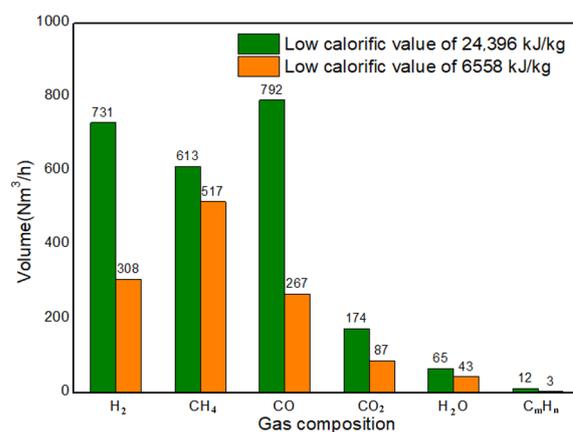


Figure 2. Composition of mixed gas of syngas and pyrolysis gas.

The high-temperature liquid ash (100 kg/h, 1773 K) entering the slag-cooling device is subjected to water bath quenching in a cold-water tank and then condenses into small solid slag particles (100 kg/h, 473 K), which can be recycled and reused. The circulating cooling water inlet parameters are 978 kg/h and 293 K, and the outlet parameters are 978 kg/h and 328.5 K.

The mixed gas (2386 Nm³/h, 643 K) from the mixing tank is first fed into the carbon monoxide conversion device (473 K), and the carbon monoxide (792 Nm³/h, 643 K) in the mixed gas reacts with the water injected into the conversion device (584 kg/h, 393.24 K, saturated steam) to generate hydrogen and carbon dioxide. The circulating cooling water is provided by the outlet cooling water of the slag-cooling device (978 kg/h, 328.5 K) to carry away the heat released by the conversion reaction. The parameters of the outlet circulating cooling water are 978 kg/h, 393.24 K, and saturated steam, of which 584 kg/h is sprayed into the conversion device to participate in the reaction, and the remaining 394 kg/h is introduced into the gasifier as the gasification agent.

The mixed gas (3113 Nm³/h, 423 K) after carbon monoxide transformation, with the gas components shown in Figure 3, enters the decarbonization unit, where carbon dioxide gas (966 Nm³/h) is separated from the mixed gas and stored or used for dry ice production. The remaining mixed gas enters the pressure swing adsorption device through a gas exhaust fan, where hydrogen gas (1523 Nm³/h) is extracted and can be sent to the tar hydrogenation device to produce light fuel oil products. The remaining mixed gas (CH₄, 624 Nm³/h) after extracting hydrogen is sent to the gas tank for storage and sale, of which 515 Nm³/h gas is fluidized gas for the pyrolysis furnace.

The equilibrium calculation results of low-calorific-value materials (1000 kg/h, calorific value of 6558 kJ/kg) are included in the above figures.

The CO conversion reaction is a common reaction in the chemical industry, which can generate CO₂ and H₂ by reacting CO with water vapor under certain conditions. CO₂ can be collected and utilized, and the hydrogen in the water can be released through the CO conversion reaction, thereby alleviating the high energy consumption and high cost of hydrogen production by the electrolysis of water. H₂ is exactly the renewable fuel or fuel-cell raw material we need, thus converting low-quality energy into high-quality energy. It can be seen in Figure 3 that after CO transformation, CO and H₂O are completely

depleted, and the contents of H₂ and CO₂ greatly increase. More specifically, for sample 1, with a higher carbon content and a low calorific value of 24,396 kJ/kg, the generation of H₂ increases by 2 times, while the generation of CO₂ increases by as much as 5 times. But for sample 2, with a lower carbon content and a low calorific value of 6558 kJ/kg, the generation of H₂ and CO₂ does not increase as significantly as sample 1. This should be related to the higher degree of reaction of samples with higher carbon contents. In addition, during the CO transformation process, CH₄ does not participate in the reaction.

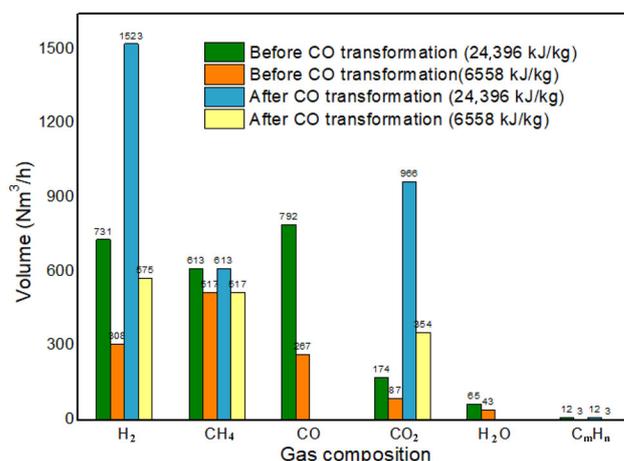


Figure 3. Composition of mixed gas after carbon monoxide transformation.

The calculation results were basically consistent with the calculation results in the literature [13], and the conclusions obtained from the calculations were consistent with the general law of pyrolysis and gasification for coal and biomass and other carbon containing materials. The calculation results show that the technical system can achieve the source and destination of materials, intermediate products, and production materials and achieve a balance between the system's heat and material income and expenditure, which can achieve the balance of the entire system. At the same time, it improves the stability, efficiency, and economy of system operation, laying a theoretical foundation for future experimental verification and practical applications.

5. Conclusions

A comprehensive treatment and resource utilization technology and system for carbon containing waste is proposed in this article. The intermediate and final products are recycled, the process is interlocked, and the simulation and balance calculation of the entire system are completed through a comprehensive two-stage-cycle treatment technological scheme. The following conclusions have been verified:

1. Carbon containing waste can provide heat for the pyrolysis process through partial oxidation and combustion. The remaining large amounts of carbon containing materials undergo normal anaerobic low-temperature pyrolysis. The semi-coke produced by the self-heating pyrolysis furnace can be directly used as a raw material for the gasification furnace, and the liquid water separated from the purified pyrolysis gas can be used as a source of cooling water in the quenching tower for recycling. The fluidized gas required for the pyrolysis furnace can come directly from the remaining gas after the pressure swing adsorption extraction of hydrogen gas.
2. The high-temperature syngas generated in the gasifier can enter the waste heat boiler for heat exchange, extracting a large amount of heat and heating the cooling water in the waste heat boiler to form saturated steam, which can be used for heating or power generation. High-temperature liquid ash can be sent to the slag-cooling device for heat exchange and can be recycled as outlet cooling water.

3. The water required for the carbon monoxide conversion device can be obtained from the outlet cooling water of the slag-cooling device. The mixed gas after CO conversion enters the decarbonization device to separate CO₂ gas, which can be stored or used to produce dry ice. The saturated steam from the CO conversion device can be used to provide the gasification agent required for the gasifier. The hydrogen extracted by the pressure swing adsorption device can be used for tar hydrogenation to produce light fuel oil products. The remaining gas mixture after extracting H₂ can be used for burning, in which a portion of the gas is the fluidized gas for the pyrolysis furnace to ensure that the bed material of the pyrolysis furnace is always in a fluidized state.

The pyrolysis–gasification two-stage-cycle process has the following advantages over the conventional single-stage pyrolysis or gasification process: (1) A variety of different types of carbon containing wastes can be mixed together for pyrolysis–gasification two-stage-cycle treatment, without the need for the classification of raw materials, thus saving the high cost of classification treatment. (2) The intermediate products produced by pyrolysis and gasification can be mutually utilized, reducing the cost of raw materials (gasification semi-coke, fluidized gas, gasifier agent, cooling water, etc.). (3) Carbon containing waste can provide a heat source for the pyrolysis process through its own partial oxidation combustion and heat release, and the heat source required by the pyrolysis furnace comes from the material itself, without the need to provide a heat source from the outside so as to reduce heating costs. (4) The pyrolysis and gasification processes are interlocked from end to end, which can realize the reduction in, resource utilization of, and harmless disposal of carbon containing wastes so as to dispose of carbon containing wastes effectively, cleanly, and at low cost and efficiently utilize carbon containing wastes. It provides an effective way to realize a low-carbon society in the future. Of course, there are some disadvantages: for example, the operation and maintenance of the system are more complex, it is difficult to achieve a balanced operation, the automation requirements are higher, and a large number of experiments and engineering verification are required before quantitative application.

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