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Performance investigation of the gasification for the kitchen waste powder in a direct current plasma reactor

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ABSTRACT

Plasma gasification is a novel gasification technology that offers a promising treatment of kitchen waste (KW) and other types of waste (e.g., medical waste). By considering the dried flour and dried rice, a high power (~35 kW) plasma gasification system for these two raw materials was achieved in this work. Then, the effects of particle sizes and plasma energy ratio (PER, the ratio of plasma energy and the low heat value of the feedstocks) for the dried rice are investigated and discussed. The particles size (<10 mesh, 10–20 mesh and 20–40 mesh) were selected to investigate their effects on the gasification process, in which the particle size (10–20 mesh) has the best performance for the concentration of carbon monoxide and hydrogen. The range of PER (0.08–0.53) was studied and indicated that the syngas reaches the peak at PER = 0.25 with corresponding concentrations of 26.6% CO and 10.0% H_2. Besides, the higher PER could also give rise to the high temperature inside the chamber, which has a safety risk for a long-time working in industrial applications.

1. Introduction

The production of kitchen waste (KW) keeps increasing with the rise of consumption in China. It has become a source of pollution that causes threats to the drinking water and daily human life. The treatment of kitchen waste has been one of the urgent problems in our time [1]. The landfills, as traditional KW disposal, have low efficiency for waste disposal, which might not meet the increase of the production of kitchen waste. Besides, KW decomposition facilitates the spread of diseases and viruses through insects and rodents [2]. Therefore, various thermal processes, including incineration, pyrolysis, and gasification, have been obtained broadly attractions due to their high disposal ability and reusable productions (e.g., syngas for power generation). In the gasification process, few pollutants are released into the environment, which not only meets the need of the environmental-friendly and sustainable consideration but also is economically suitable for handling a large amount of waste [2,3]. In addition, as reported in Ref. [4], a cruise ship generates up to 3.5 kg/person-day and with around 3800 passengers (including staff) produces annually around 1700 m^3 of food waste, accounting for around 22% of the total waste produced on board. Thus, processing food waste is an important aspect of sustainable tourism. More specially, naval ships and submarines are designed to make the most use of space to install the devices for protecting national interests at sea. This means that there is little room available for kitchen waste handling and post-processing equipment, which are also required for rapid startup and shutdown [5]. Equally important, low emission of waste gas from thermal treatments is also required for the at-sea treatment of naval ships kitchen wastes, avoiding the naval ships and submarines being detected as a military target. This incongruity between kitchen waste disposal and the primary mission of naval ships is eager to develop advanced technologies for the at-sea treatment of shipboard kitchen wastes [6]. Thus, incineration, plasma gasification or other thermal treatments become a preferred method for waste disposal.

The gasification is achieved by reacting the feedstock material at high temperatures (typically >700 °C) via controlling the amount of injection oxygen and/or steam into the reaction [7]. The high temperature plays a vital role in the gasification process. Thus, the plasma is used to achieve a high operating temperature for converting organic materials into syngas within an oxidant starved environment, namely the plasma gasification technology. As reported in Ref. [8], the temperature in the core of a typical direct current (DC) plasma jet could reach 30,000 K. Besides, during the gasification process, the extremely

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high temperature decomposes some toxic components (e.g., dioxin) to harmless chemical molecules [9,10], which avoids complex and expensive post-processing apparatus compared with the traditional gasification. It is also considered to be the most cost-effective approach available and among the safest, requiring little specialized personnel training [5]. Therefore, the plasma gasification technology has attracted the attention of shipboard waste disposal due to its low emission of waste gas, high volume reduction, easy operation and small required space [5,6].

In previous studies, plasma gasification had been achieved through a radio frequency (RF) induction plasma, a microwave (MW) plasma, an alternating current (AC) plasma, and a direct current (DC) plasma. Tang et al. [11] studied biomass gasification using an RF plasma technology with 1.6–2.0 kW and concluded that the conversion of the biomass feed to syngas is enhanced by high input power, operating pressure, and shorter electrode distance. Furthermore, Huang and Tang [12] reported a pyrolysis treatment of waste tire powder in an RF plasma reactor. For different powder sizes, i.e., 200 mm and 600 mm, the solid conversion ranges from 40% to 78.4% over the given input power of 1.6–2.0 kW. As for the MW plasma, Yoon et al. [13] performed the plasma gasification of coal and charcoal by a 5 kW microwave steam and air plasma torch, in which they found carbon conversion increased as the oxygen/fuel ratio increased, and cold gas efficiency was maximized when the oxygen//-fuel ratio was 0.272. Hong et al. [14] investigated the gasification of brown coal in a 4 kW microwave steam plasma torch and noted that the further increase of coal to steam ratio did not much reduce carbon dioxide concentration. Sekiguchi et al. [15] studied the gasification of polyethene pellet using atmospheric argon-steam microwave plasma, demonstrating that additional steam to argon plasma enhances syngas production. Rutberg et al. [16] achieved the gasification of the wood with 20% moisture by an air AC plasma torch and analyzed the energy consumption of the plasma process, which can be the basis for the prospects of large-scale industrial plants. Subsequently, they [17] investigated the long-time gasification of plastic by a 100 kW steam-air plasma torch. The cold gas efficiency can be over 82%, the content of valuable gas (e.g., CO, H_2, CH_4, et al.) in the syngas reaches more than 88%.

For the DC plasma gasification, Van Oost et al. [18] experimentally investigated the gasification/pyrolysis of biomass using DC arc Ar–water plasma and give a prospect of plasma gasification technology for the biomass treatment in science and industry. Lee et al. [19] investigated the production of syngas for coal gasification using a DC non-transferred steam plasma system. The effects of the coal feeding rate on cold gas efficiency, carbon conversion, and hydrogen conversion were evaluated by the amount of syngas from two kinds of coals. In the study [20], the thermal plasma generated by DC plasma was used as a heat source, where steam was added to react with carbon. Graphite was used as a test piece instead of carbonized wastes. The result indicated that it is possible to reduce the weight of graphite and to produce combustible gas from graphite by using the DC steam plasma. Hlina et al. [21] performed the plasma gasification of biomass (spruce sawdust, wood pellets) and waste (waste plastics, pyrolysis oil) through a 100–110 kW H_2O/Ar DC plasma torch. They achieved high content of CO and H_2 but pointed out high demand for electricity in this technology. Li et al. [22] used the lab-scale 1 kW plasma reactor to carry out the air and steam gasification for the mixtures of flour and vegetables, in which the optimal air equivalence ratio and steam feedstock ratio are 0.095 and 0.084, respectively. Ma et al. [23] investigated a DC plasma steam gasification for the mixtures of wood sawdust and high-density polyethene with different input plasma powers (16–24 kW) and varying steam flow/carbon flow ratios (0.2–1.8), they obtained high content of hydrogen in syngas productions and found that the input power has the largest correlation with the increase of H_2 yield. Subsequently, based on this plasma gasification process, they [24] studied a tar evolution and showed that the light/heavy polycyclic aromatic hydrocarbons are the dominant compounds in the tars. Besides, Inaba et al. [25] mentioned that the application of thermal plasma to waste treatment may be a possible method for treating various kinds of hazardous waste, in which the hazardous waste can be converted into blocks of vitrified slag. Subsequently, Kim et al. [26] performed a test of vitrified slag's safety by a DC non-transferred arc and reported the properties of slags were affected by differences in the cooling methods. Chu et al. [27] performed thermal plasma treatment of a mixture of Fibre reinforced polymeric matrix composite (FRPC) materials, gill net and waste glass by Argon DC non-transferred plasma furnace. With the air as ambient gas, the vitrification process was achieved and revealed that their results could be comparable with the commercial products.

Fig. 1. The picture of 35 kW plasma torch.

Concurrently, Janajreh et al. [28] developed a model for the DC plasma gasification using Aspen Plus and applied it for waste tire material, coal, plywood, pine needles, oil shale, and municipal solid waste, algae, treated/untreated wood, among which the average process efficiency is around 42%. Many other modeling studies have investigated the impact of different feedstock materials and operating variables on syngas properties during the plasma gasification. Mountouris et al. [29,30] developed an equilibrium thermodynamic model to study the plasma gasification process of two biomass materials and analyzed the performance of integrating the optimum plasma gasification system with a gas turbine combined cycle. This system has a higher efficiency than conventional technologies based on waste incineration, which is intrusive for industrial applications of plasma gasification. Through simulation models, Zhang et al. [31] and Favas et al. [32] systematically investigated the gasification parameters (e.g., air equivalence ratio, steam feedstock ratio) and efficiency in terms of the plasma gasification process under different operation conditions. Overall, previous studies have begun to devote to applying plasma gasification into the industry for different raw materials. Herein, a plasma gasification reactor was designed and employed to gasify rice powder and flour powder (replace main components of the KW) in cruises and naval ships. This plasma gasification system has the properties of simplification, easy operation, steadiness, strong processing ability and rapid startup and shutdown. This work's objective is to develop a continuous gasification method for KW materials while also providing an experimental dataset for plasma gasification modeling and industrial applications.

This paper is organized as follows: we give detailed descriptions of the plasma torch and gasification setups in Section 2. Experimental results are presented and discussed in Section 3, which is divided into three parts. In the first part, the gasification of rice powder and flour powder are respectively achieved and compared with each other. And in the second part, we investigate the effects of different powder sizes of

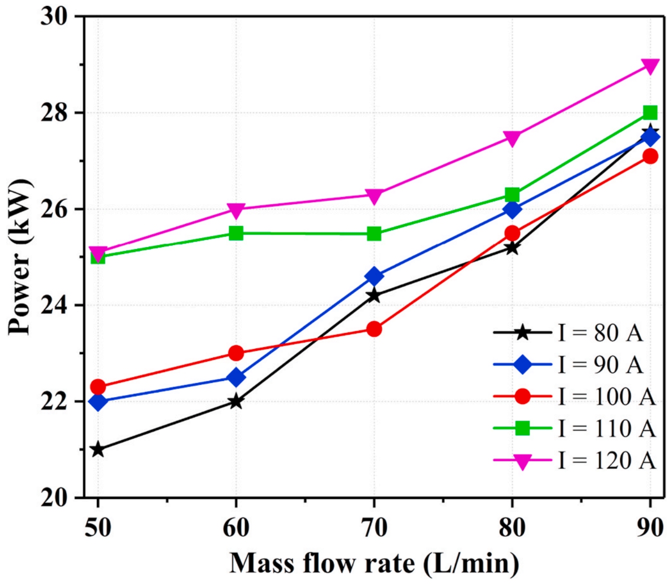

Fig. 2. The power of the plasma torch with different gas flow rates. The power is a time-average result. In order to protect the plasma torch, the maximum power of 35 kW is not tested. And the mass flow rate of 50 L/min and current 80 A are the lowest requirements for the normal work of a plasma torch. Note that the efficiency of the power is not considered in this figure.

rice on the gasification performance. In the last part, we discuss the effects of different plasma input powers on gasification performance. The economic analysis is also shown in this Section. Finally, the conclusion is summarized in Section 4.

2. Experiment devices

The plasma generator system was researched by the Institute of Mechanics, Chinese Academy of Sciences, and the maximum power is about 35 kW. Based on the estimated processability of this torch, we designed the gasification chamber and other elements for the gasification.

2.1. Plasma torch

The DC plasma torch is shown in Fig. 1. It mainly consists of an insulator, an anode, and a cathode, respectively, surrounded by water-cooling channels to protect them from erosion induced by high temperature. Nitrogen is used as a working gas because of its inertion for electrode material despite that it is a little hard to be ionized. The high voltage between anode and cathode generates an electric arc. The continuous input working gas makes the electric arc keep stable and flows outward the nozzle as a high-temperature and high-velocity plasma jet.

Fig. 2 demonstrates that the variation of plasma torch power under different nitrogen mass flow rates. The mass flow rate of 50 L/min is the lowest requirement for the normal work of the plasma torch. If the mass flow rate is lower than this, the heat caused by the plasma jet cannot be brought out by the working gas and possibly gathers into the nozzle of the plasma torch, which is apt to ablate the anode and cathode. The plasma torch power rises gradually with the increase of flow rate or with a higher current. Unfortunately, a higher current reduces the life of the anode and cathode. As for a smaller current, the formed plasma jet has a short and narrow profile, and even arc break could happen, in which the small energy density of the plasma is of low efficiency for gasification. During the experiments, the parameters (mass flow rate and current) match the ranges in Fig. 2.

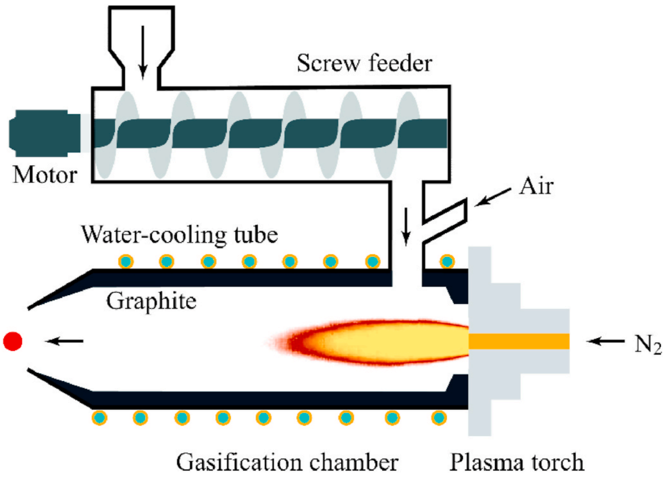

Fig. 3. The sketch of the plasma gasification chamber. The arrow direction denotes the flow direction of feedstocks and gas. The graphite is used to enhance heat transfer, and the water-cooling tube avoids extremely high temperatures in the gasification. During the experiments, the screw feeder is sealed, and we use an exhaust fan (which is not shown in the sketch) at the end to form a slight negative pressure condition for the gasification. The red point shows the positions of the gas analyzer and platinum-rhodium thermocouple. (For interpretation of the references to colour/colour in this figure legend, the reader is referred to the Web version of this article.)

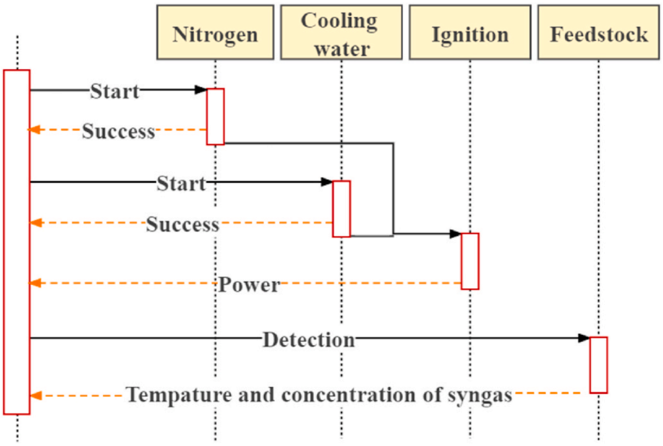

Fig. 4. The sequence diagram of the 35 kW plasma gasification process.

2.2. Gasification chamber

Fig. 3 shows a schematic of the plasma gasification process. A screw feeder is used to feed the food powder into the gasification chamber. The average mass flow rate of the screw feeder during the experiments is 5 kg/h. There is a branch for air injection at the side of the inlet channel, whose flow rate is decided by the air-fuel equivalence ratio. The gasification chamber has a cylindrical shape with an inner diameter of 160 mm and a length of 500 mm, which was fabricated with stainless steel (Type 312). The chamber is connected with the plasma torch through a flange. The cooling system for the gasification process is required due to the high temperature of the plasma torch. The chamber was encircled on all sides by a copper tube with water of approximately 3 m^3/h. A hollow cylinder (thickness 20 mm) of graphite material was attached near the chamber's wall. The graphite endured high temperature and enhanced the heat transfer between the chamber and the cooling copper tube, which avoided the high temperature in the gasification chamber. Based on this design, the present plasma system can safely achieve the long-time steady working. At the end of the gasification chamber, the

Table 1
Drying and reactor energy consumption with different target moisture contents (based on 1 kg raw material with 80% initial moisture content).

Target moisture content	%	40	30	20	10
The energy consumption during the dry process	kWh	0.53	0.56	0.59	0.61
The energy consumption of the reactor	kWh	1.27	1.22	1.19	1.16

platinum-rhodium thermocouple was used to get the gasification temperature. We used FTIR spectroscopic gas analyzer (Gasmet DX-4000) and Hydrogen Analyzer (QRD-1102C) to collect and detect the contents of the gasification gas. Concurrently, an exhaust fan is employed to form a negative pressure condition for the gasification process. The experimental procedure is shown in Fig. 4. In the beginning, we open the nitrogen and the cooling water. Once we receive the feedback (success) of nitrogen and cooling water, the plasma torch can be ignited and the experiment can begin. The gas analyzer and thermocouple can be used to detect the concentration and temperature of the syngas, respectively.

3. Results and discussion

For the simplicity of the study, we used rice powder and flour powder to replace the main components of the KW. Based on the devices mentioned above, two feedstocks are gasified, respectively. Subsequently, two critical parameters for plasma gasification, i.e., particle size and plasma input energy, are investigated. The productions of syngas below are the time-average values among the 10-min tests.

3.1. *The gasification of rice and flour*

Here, we only compare the gasification production of flour and rice after drying. Table 1 estimates that the consumption energy of the drying process and gasification. We assume that 1 kg raw material has an initial moisture content of 80%. And the heat capacity and the specific latent heat of water are 4.2 kJ/(kg·°C) and 2500 kJ/kg, respectively. As shown in Table 1, the consumption energy of the drying process increases from 0.526 to 0.611 kWh to achieve different target moisture content. As for the energy consumption of the reactor, here we assume the power efficiency of the reactor is 75%, including the heat loss of cooling water and the reactor. And the average low heat value (15.29 MJ) in Table 2 is adopted to estimate the energy consumption during the gasification. Overall, the energy consumption of the reactor is about 1.2 kWh. Based on our experiments, they have the mass flow rate of the feedstock of 5 kg/h. The consumption energy of the process per hour approximates 8.98 kWh, while the input energy per hour of the plasma system is 30 kWh according to normal power. The latter is much large than the consumption energy during the process, which means that the power of the plasma torch is enough for feedstock drying and gasification. In previous studies, the moisture content is recommended to be below 40% for optimal gasification and safety (it will produce large content H_2 if the moisture content is over 40%). Thus, in this study, we only compare the gasification production of flour and rice with low moisture content for safety.

To obtain the same particles size and moisture, we firstly mix the raw materials with water and then dry and mill them. The ultimate analysis and experiments parameters for the materials are shown in Table 2. The average mass flow rates of the screw feeder for two materials are both 5 kg/h. Parameter PER means the plasma energy ratio, which will be introduced in Section 3.3. Parameter ER denotes the air-fuel equivalence ratio. Here, the number 0.10 is selected based on our previous study [22]. The syngas results are demonstrated in Fig. 5. The concentrations of CO_2, H_2, and CO_2 in flour are larger than those in rice. The other components are approximately close. This is due to the high ratio of O/C in the flour, which further promotes the gasification process. And then, a part of the produced CO is further combusted to CO_2.

3.2. *The effects of the particle size of a feedstock*

The particle size of the feedstock determines the interface between the feedstock and the high-temperature plasma, where gasification reactions happen and produce the syngas. Thus, the particle size is crucial to syngas production and gasification efficiency. Before the experiments, the rice was broken and selected by the sieve series with Tyler mesh sizes of 10, 20, and 40. Thus, Case1 (<10 mesh), Case2 (10–20 mesh), and Case3 (20–40) were selected to study the effects of the particle size on the gasification process. As shown in Fig. 6, the particle size in Case2 has the best performance of the gasification, in which the CO concentration reaches 23.38%, while the concentrations in the other two cases are 17.2% and 16.5%, respectively. The concentration of the H_2 almost keeps the same among these three cases. The particle size in Case 3 is the smallest and lightest, which are easily engulfed and brought to the end of the chamber by the plasma jet flow. Therefore, a number of the particles demand great efforts to reach the center of the plasma torch. Consequently, in the chamber, the short residence time and the low-temperature atmosphere of the particles are difficult to support the complete gasification, which might give rise to the Boudouard reaction and tar cracking are dominated in the gasification, as shown in a chemical reaction (1). Finally, the productions of CH_4 and C_xH_y are a little higher in Case 3.

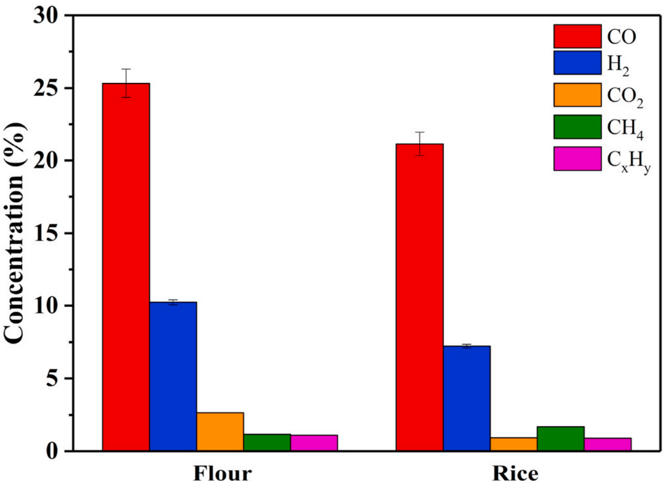

Fig. 5. The syngas production of gasification for flour and rice powder.

Table 2
Ultimate analysis and experimental parameters for rice and flour, respectively.

Processed feedstocks	C	H	O	N	S	LHV	PER	Mesh	ER	Moisture
	%					MJ/kg				%
Rice	40.86	6.63	34.27	4.52	< 0.1	14.9	0.1277	10–20	0.10	12.3
Flour	40.03	6.88	47.59	1.99	< 0.1	15.64	0.127	10–20	0.10	12.1

Note: ER: air-fuel equivalence ratio; PER: plasma energy ratio, see Section 3.3.

$$Tar \rightarrow CH_4 + H_2 + H_2O + C_xH_y \quad (1)$$

With the increase of the particle size, i.e., in Case 2, the feedstock particles can reach the center of the plasma torch. It gives rise to the higher temperature and higher temperature gradient inside particles, resulting in better reaction rates during gasification than that of particles with a bigger size. Thus, high operating temperatures improve the conversion of tar or char into light gases through reaction (1). As for Case1, the particle becomes heavy and gets through the center of the plasma torch. However, due to the particles sizes being large, the gasification may happen on the surface, while most inside materials have no time to react with the plasma torch before they arrive at the bottom of the chamber. Moreover, as reported in Ref. [33], the residence time of the volatiles generated during the gasification would be much longer in a large particle than in a small particle. More volatiles would recondense or reabsorb on the internal surface of the char from a large particle than that from a small particle, resulting in increases in the char yield. Note also that a number of the unreacted residuals, including char, are observed after the experiments of Case1. As a result, the gasification for the particles in Case 1 is not uniform, and CO production decreases.

3.3. *The effects of plasma energy ratio (PER)*

The input power of the plasma torch plays a crucial role in gasification. The high plasma torch power brings higher electrical energy density into the gasification chamber and provides higher temperature for the gasification process, which is helpful to improve the production of CO and H_2. On the other hand, the gasification efficiency is also limited by the feeding speed of the material. For a given power of the plasma torch, if the feeding speed is slow, and the power is larger than that gasification needs, which causes the waste of the input energy. On the contrary, if the feeding speed is fast, which possibly is over the consumption-ability of the plasma torch, some material would stay and be accumulated in the chamber, subsequently affecting the normal working of the plasma torch. Therefore, the plasma energy ratio (PER) [31] is introduced in this study to investigate the gasification process, as follow:

$$PER = \frac{P_{plasma}}{LHV_{feedstock} \times \dot{m}_{feedstock}} \quad (2)$$

The P_{plasma} is the input power of the plasma torch, $LHV_{feedstock}$ is the low heat value of the material, and $\dot{m}_{feedstock}$ is the mass flow rate of the feedstock.

During the experiments, the particle sizes of feedstock are 10–20 mesh. As shown in Fig. 7, the concentrations of CO and H_2 have an increasing trend with a following of a decrease, where the concentrations reach the peak at the location PER = 0.25. When PER rises from 0.08 to 0.25, CO concentration increases from 17.7% to 26.67%, whereas H_2 concentration has a slight increase, remaining in the range of 7.5% to 10.0%. The increase of the input power of the plasma torch brings in more energy and a higher temperature (see pink-circle line) for the gasification process. The thermal decomposition of heavy hydrocarbons, e.g., tar and char, are enhanced at high operating temperatures. As a result, the gasification process is enhanced and the production of the syngas is improved in the high-temperature atmosphere. As the PER increases further, from 0.25 to 0.51, the concentrations of CO and H_2 gradually decrease, while the concentration of CO_2 still increases from 0.56% to 4.81%. At high PER, more plasma energy gives rise to a high operation temperature, the decrease in CO content could be due to reverse water-gas reaction [33]. For the decreasing trend of H_2, the reverse water-gas reaction could consume a few H_2 [34]. On the other hand, the plasma radicals of N_2, e.g. N+, might play an important role during the gasification at high PER. That means from the reaction of N+ with H_2, the NH radicals are produced and further generate the NH_3 during the gasification process, as reported in Ref. [35]. Similarly, Ma et al. [23] reported that the high input power of the reactor favors the gasification of tar and leads to a rapid increase in H_2 yield, but the average H_2 yield also has an approximate decreasing trend when the input power is high. And the trend of syngas content in small PER is similar with the study of [31], in which it showed that the CO and H_2 concentrations increased with the rise of the PER (0–0.26), ascribing to the tar cracking. But the effects of higher PER on the gasification were not reported. Nevertheless, other similar studies [18,34] also have shown that a smooth decrease in H_2 yield occurs at very high reaction temperatures. Overall, the cause of the decreasing trend needs more

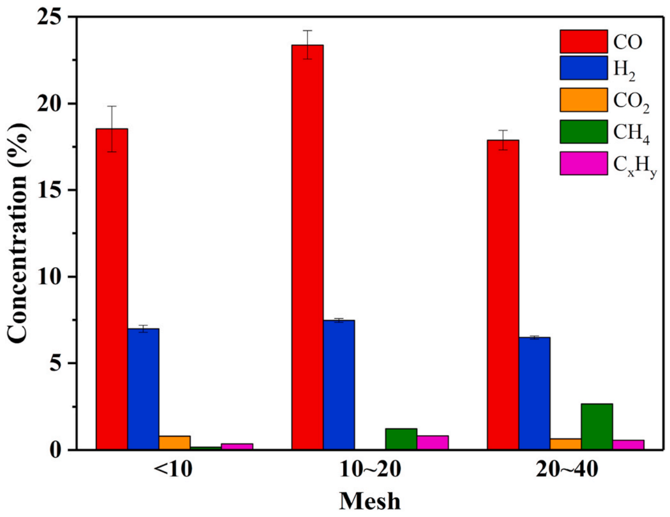

Fig. 6. The gasification effects with particle sizes.

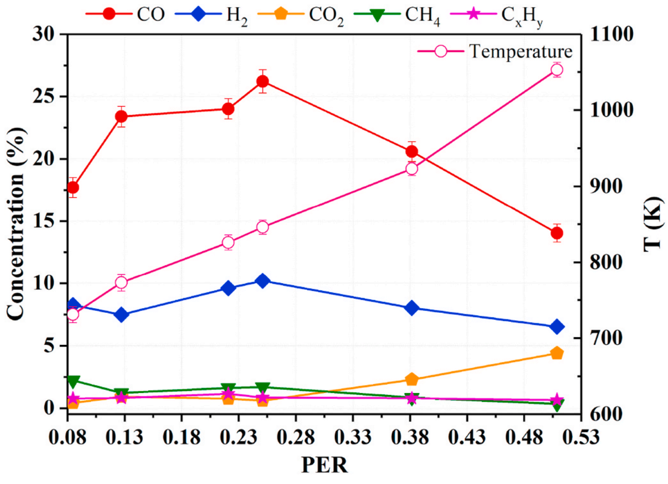

Fig. 7. The syngas production with the increase of PER. The standard deviation of the concentration and temperature along the time is assumed as the measurement error. For clear display, the measurement error of the temperature is enlarged 5 times.

Table 3
The capital costs of 35 kW kitchen waste gasification system built in China (10^4 Yuan RMB).

Name	Description	Cost
Gasifier	Materials and manufacture	0.35
Cooling water	Installation, water tank and tube	0.20
Plasma system	Plasma torch, electric source and mass flow rate controller	35
Monitor system	Instruments and control equipment	1
Total		31.55

Note: 6.40 Yuan RMB = 1 USD.

Table 4
Running cost of 35 kW kitchen waste gasification in China (per day).

Name	Unit	Value
Operation time (at night)	Hour	12
Kitchen waste	kg	60
The electrical consumption (maximum power) of the plasma torch	kWh	420
The electrical consumption of drying	kWh	31.4
Electrical cost	Yuan RMB	103.8
Personnel cost	Yuan RMB	100
Maintenance cost (including Consumables)	Yuan RMB	50
Cost per kWh	Yuan/kWh	0.68

Note: The amount of kitchen waste (about 30 people) is estimated according to Ref. [4].

investigation. Note also that the high PER would lead to the high temperature, which is not suitable for the long-time working in engineering, e.g., as mentioned in Ref. [31], the chamber temperature reaches approximately 1600 K when PER = 0.26. This temperature is already too high for an engineering application.

3.4. Economic analysis

Table 3 gives the investment components for the 35 kW plasma gasification system. The investment mainly concentrates on the plasma system, which is the key technology of the system. From the table, we can learn that the unit investment of this 35 kW system is about 9443 Yuan RMB/kW, which is higher than that in the traditional biomass gasification system [36]. But compared to these traditional gasification systems, the present plasma gasification occupies a small working area and hardly requires investment in gas cleaning and waste cleaning. The syngas during the gasification can also be recycled through combined gas engines. Thus, for some special applications, e.g., naval ships and oceangoing cruises, the green and environmentally-friendly properties of this technology has a great advantage. As for the running (operation) cost, this small-scale plasma gasification is simple, easy-handle for operators, steady and has a strong processing ability on kitchen waste. The system does not need consistent running to keep the high temperature of the gasification chamber. It can achieve rapid startup and shutdown. Thus, the costs of the maintenance, personnel and electrical consumption are low, as shown in Table 4. Finally, the running cost of the whole system is about 0.68 Yuan/kWh/day, which has an economic attraction in many industries.

4. Conclusion

In this paper, we introduce an investigation of a high-power plasma gasification system for kitchen waste. We compare the gasification production of dried flour and dried rice. The dried flour has a better gasification performance because of the high ratio of O/C. Subsequently, the study mainly focuses on the influence of the feedstock particle size and plasma energy ratio. The results showed that particle size has effects on the gasification process. During the experiments, the particles size (<10 mesh, 10–20 mesh, and 20–40 mesh) was used, and the particle size (10–20 mesh) has the best performance with the concentration for CO 23.36% and H_2 8%. As for the plasma energy ratio (PER, the ratio of plasma energy, and the low heat value of the feedstocks), the range of the PER, from 0.08 to 0.53, was achieved. The syngas concentrations have an increasing trend when the PER rises from 0.08 to 0.25. Subsequently, the syngas concentrations begin to decrease with the increase of the PER (from 0.25 to 0.53). It demonstrates that the syngas reaches the peak at PER = 0.25, where the concentrations of CO and H_2 are 26.6% and 10.0%, respectively. We also estimated that the running cost of the whole system is about 0.68 Yuan/kWh/day, which has an economic attraction in many industries.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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