NUMERICAL SIMULATION OF PLASMA GASIFICATION OF OIL-BASED DRILLING CUTTINGS

by

Liang HU[a], Hailong YU[a*], Yayun XU[a], Xinying DUAN[a], Xulei WU[a], Yunlan SUN[a], Haiqun CHEN[a*], He ZHENG[b], and Bo WU[c]

[a] School of Petroleum Engineering, Changzhou University, Changzhou, China
[b] Sinopec East China Petroleum Engineering Co., LTD. Jiangsu Drilling Company, Nanjing, China
[c] East China Petroleum Engineering Company, Sinopec, Nanjing, China

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In this paper, ASPEN PLUS commercial software is used to simulate the plasma gasification process of oil-based drilling cuttings, and the numerical simulation results are analyzed in detail. The conclusions can provide theoretical guidance for subsequent experiments and practical engineering applications. A set of reactor models suitable for gasification of such substances was established by using Gibbs' free energy minimization principle, and the accuracy of the model was verified by comparing the numerical simulation results with the experimental results. In this model, the effects of plasma torch power, air equivalent ratio, moisture content of feed, and the amount of CO_2 added on the gasification results were simulated. Through systematic analysis, the optimal gasification parameters are determined output power of plasma torch is 27.5 kW, air equivalent ratio is 0.26, moisture content of feed is 6%, and the amount of CO_2 added is 6 kg per hour.

Key words: *ASPEN PLUS, plasma, oil-based drilling cuttings, gasification*

Introduction

In recent years, with the Chinese government's continuous improvement of environmental protection requirements, treatment standards for oil-based drilling cuttings (OBDC) generated during the oil and gas production process have also improved in recent years, which requires the development of a set of efficient treatment schemes. High temperature plasma is used to gasify and melt OBDC [1, 2], which can decompose the toxic and harmful substances in OBDC at high temperatures and melt the solid products into glassy state molten slag to avoid secondary pollution. Recycling can be met by the products after processing (syngas and slag) [3]. The multi-carbon macromolecular organic matter in the OBDC is rapidly pyrolyzed in the gasifier to generate small-molecule syngas while the slag forms a stable glassy state molten slag after quenching [4], and the heavy metals are wrapped by the vitreous components with extremely low permeability, which can be used for resource utilization or directly buried safely. The primary emphasis of this research is the gasification of OBDC.

The ASPEN PLUS is a large-scale simulation system commonly used for chemical process simulation, which originated from the Massachusetts Institute of Technology. It is also widely used to simulate various gasification processes. The application of ASPEN PLUS to

* Corresponding authors, e-mail: yhl.doctor@163.com, chenhq@cczu.edu.cn

simulate the treatment of solid waste by plasma gasification systems is widely used throughout the world. Agon *et al* [5] used ASPEN PLUS to simulate the plasma gasification process of garbage-derived fuel and plastic solid waste. In this regard, many scholars in China are also studying ASPEN PLUS, and it can accurately simulate the impact of different factors on the gasification process.

At present, ASPEN PLUS is used to simulate the pyrolysis and gasification processes of biomass, municipal solid waste, oily sludge, *etc*. [6-10], and OBDC is relatively few to study. The main purpose of this paper is to analyze the influence of plasma equipment parameters on the gasification of OBDC. The model used is different from some models in other papers, which is more consistent with the actual working condition of the plasma reactor. In this model, the temperature of low temperature reactor (LTR) changes with high temperature reactor (HTR), which is obviously more reasonable than the fixed temperature of LTH in most papers. Furthermore, the majority of the present models focus on the impact of temperature on the gasification outcomes but neglect to account for the impact of a change in the carrier gas with power on those outcomes, which is inconsistent with plasma reactors' unique properties. In this paper, when analyzing the influence of power on gasification results, the carrier gas-flow also follows the change of power, which accords with the actual situation in operation. For the next tests and real-world engineering applications, this study can therefore, offer a more accurate reference and theoretical foundation.

Establishment and verification of the model

Modelling

Three reactors (pyrolytic gasification, recombination) were used to simulate the OBDC gasification process. The following is a model flow chart of OBDC pyrolysis and gasification in plasma gasifier referring to the EPJ plasma gasification model used by Luca *et al.* [11], as shown in fig. 1.

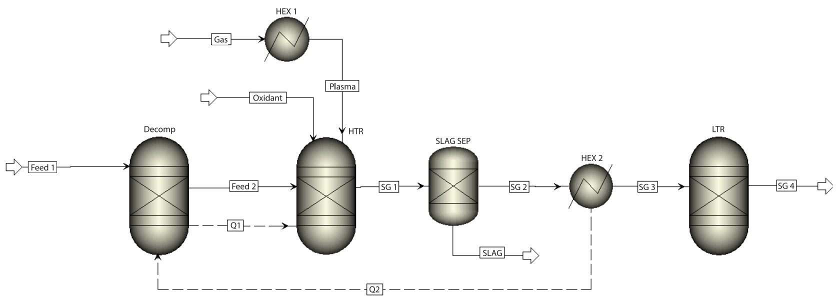

Figure 1. Model flow diagram of plasma gasified OBDC

Prior to using ASPEN PLUS to simulate OBDC pyrolysis, the main components involved in the reaction need to be known and their physical properties determined. For unconventional components, different calculation models need to be selected [12]. For this model, the physical property method is RKS-BM, and The HCOALGEN enthalpy model and the DCOALIGT density model are adopted. Input data for industrial analysis, element analysis, and sulfur element analysis of FEED1 via the PROXANAL, ULTANAL, and SULFANAL options in the NC solid tab. The model is based on the following assumptions during the OBDC gasification process: the gasification process is stable. The pressure and temperature at each point in the reactor are equal, and the parameters do not change with the reaction time. The pressure drop and pressure loss in each process and the heat dissipation loss in the reaction process are not considered. Each reaction process can be completed quickly and fully. Organic elements in OBDC can be completely vaporized. The non-gasification part of waste OBDC in the reaction is regarded as ash and does not participate in the reaction [13].

The gasifier will be simulated by three reactors, DECOMP (pyrolysis reactor), HTR and LTR, according to the temperature field distribution characteristics in the plasma gasifier [14]. The pyrolysis reactor only considers the total mass balance and reacts according to the yield relationship between the inputs. The organic matter is pyrolyzed into its basic elements. By the principle of Gibbs free energy minimization, the system composition and phase distribution are calculated when chemical equilibrium and phase equilibrium are simultaneously reached in high temperature and low temperature reactors. To simulate the heat transfer in the gasifier, the energy transfer is established in the model. Using HEX1 to heat GAS to simulate high temperature jets from plasma torches, and the thermal power of GAS transfer was used to simulate the output power in the furnace.

Validating models

To verify the reliability of the model, the model will be used to simulate the experiments in the Agon's paper [5], and the simulation results will be compared with the experimental data. This document provides experimental data on the gasification of refuse-derived fuels (RDF) at high temperatures, and its industrial analysis and elemental analysis are shown in tab. 1.

Table 1. Industrial analysis and elemental analysis of RDF

Industrial analysis [%]				Elemental analysis [%]						LHV [MJkg^{-1}]
M_{ad}	FC_{ad}	A_{ad}	V_{ad}	C	H	O	N	Cl	S	
4.60	8.60	22.10	69.30	46.80	5.70	22.30	1.25	1.60	0.26	22.37

Model parameter setting: the feed rate was 29 kg per hour, the power was 70 kW, and the flow rates of Ar, CO_2, and O_2 in the GAS gas were 87 Lpm, 177 Lpm, and 93 Lpm, respectively.

The comparison results of simulated data and experimental data are shown in tab. 2. In the simulation results, the error range of syngas components except CH_4 is within 8%, which indicates that the model is suitable for the simulation of similar plasma gasification processes within the error range.

Table 2. Simulation data were compared with experimental data

Volume fraction of syngas [%]	Experimental data [%]	Simulation data [%]	Error [%]
H_2	30.0	27.90	7.00%
CO	46.1	49.60	7.60%
CO_2	11.0	11.63	5.70%
CH_4	2.50	0.84	66.35%
Ar	10.04	10.40	3.49%

Setting simulation conditions

Taking OBDC from an oilfield in Jiangsu province as raw materials, the aforementioned model is applied to simulate the calculation. The industrial analysis and elemental analysis of OBDC are shown in tab. 3.

Table 3. Industrial analysis and elemental analysis of OBDC

Industrial analysis [%]				Elemental analysis [%]						LHV [MJkg^{-1}]
M_{ad}	FC_{ad}	A_{ad}	V_{ad}	C	H	O	N	Cl	S	
3.05	2.38	74.42	20.15	13.70	1.85	7.81	1.17	0.37	0.68	7.20

In this simulation, the feed rate of OBDC was set at 50 kg per hour, and N_2 was used as an inert medium in the plasma torch. To ensure the safety and reliability of the plasma torch at different output powers, N_2 gas intake should be positively correlated with the output power. The pressure of each part was 1 bar throughout the simulation.

The gasification of OBDC in a high temperature plasma gasifier is influenced by system parameters and the atmosphere in the furnace, such as plasma torch power, oxygen equivalent ratio, and so on, and is primarily manifested as syngas composition, carbon conversion, syngas calorific value, and plasma gasification efficiency [15].

The ratio of syngas heat generated in the gasification process to the calorific and consumed by OBDC reflects the energy utilization in the plasma gasification process.

Plasma gasification efficiency is the ratio of the calorific of syngas to the sum of heat generated by OBDC and heat consumed in the process of gasification, which reflects the energy utilization rate in plasma gasification process:

$$\eta_P = \frac{m_s LHV_s}{m_f LHV_f + \dfrac{W_T}{\eta_e}} \times 100\% \tag{1}$$

where η_P [%] is the plasma gasification efficiency, m_s [Nm^{3}hr^{-1}] – the syngas mass-flow rate, measured, LHV_s [MJN^{-1}m^{-3}] – the syngas low calorific value, measured, m_f [kghr-1] – the feeding rate of OBDC, LHV_f [MJkg^{-1}] – the low calorific value of OBDC, measured, W_T [MW] – the plasma torch's output power, and η_e – the average efficiency of the power plant, which is 34.5% by default in this paper [16].

Results and analysis

Effect of plasma torch output power on gasification results

To study the influence of plasma torch output power on OBDC gasification results, the simulated conditions are set The feeding rate for OBDC is 50 kg per hour, the temperature is 25 °C, the pressure is 1 bar, and ratio of the actual value of oxygen to the theoretical value, equivalence ratio, ER = 0.2.

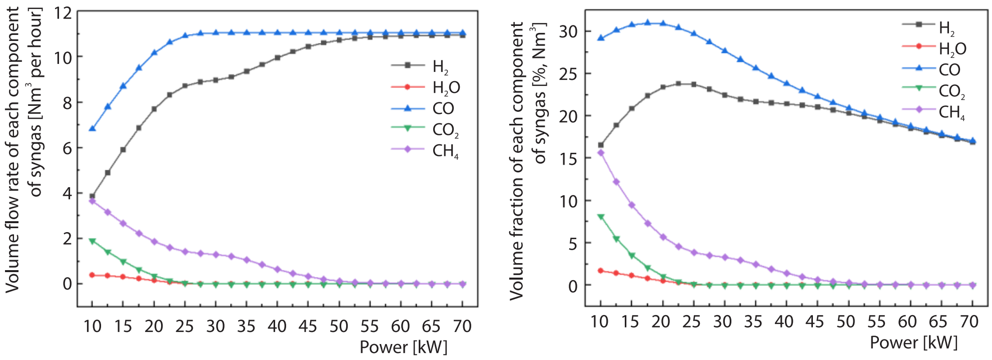

Figure 2. The effect of output power on syngas composition

As can be seen from the figure, with the increase of power, the volume flows of CO and H_2 continue to increase, while the volume flows of CO_2 and CH_4 continue to decrease. The increase in output power enhances the endothermic reactions $C + O \rightarrow 2O$, $C + H_2O \rightarrow O + H_2$, and $CH_4 + H_2O \rightarrow CO + 3H_2$ [17]. The increase in the output power of the plasma torch promotes the generation of H_2 and CO. However, it can be seen from the figure that the volume fraction of CO and H_2 in the syngas decreases continuously when the output power of the plasma torch increases to 27.5 kW. This is the reason that with the increase of power, the carrier gas into the furnace also increases, increasing the total amount of syngas, so the volume fraction of CO and H_2 begins to decrease [18].

As shown in fig. 3, the calorific value of syngas decreases with the increase of power, while the calorific value of syngas increases first and then decreases with the increase of power, reaching its peak value when the power is at 27.5 kW. With the change of plasma torch output power, the carbon conversion rate of OBDC remains unchanged at 10-27.5 kW and then begins to decrease. The efficiency of plasma gasification decreases with the increase of power, indicating that the energy utilization rate of plasma torch decreases. Under the condition of ensuring normal pyrolysis of the system, the output power of the plasma torch should be controlled as small as possible, which is beneficial to saving electricity.

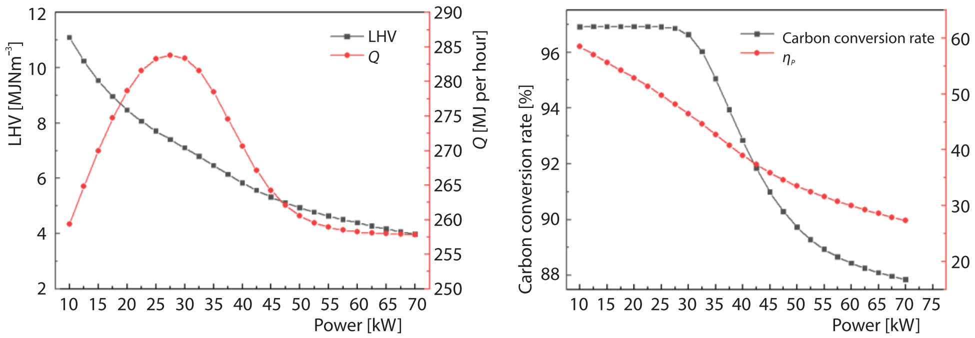

Figure 3. Influence of power on gasification effect

Effect of ER on gasification results

To study the influence of ER on OBDC gasification results, the simulated conditions are set the feeding rate for OBDC is 50 kg per hour, the temperature is 25 °C, the pressure is 1 bar, ER varies from 0-1, and the output power of the plasma torch is 30 kW.

Figure 4 shows the influence of ER on syngas components. The CO and H_2 increase continuously when ER < 0.26, and the volume fractions of CO and H_2 begin to decrease when ER > 0.26. However, CH_4 decreases with the increase of ER, and reaches the lowest when ER = 0.26. The changing trend of CO_2 and H_2O was opposite to that of CH_4 and began to increase when ER > 0.26. The reason for this change in syngas composition is that with the increase of ER, reactions $C + H_2O \rightarrow O + H_2$, $2CH_4 + O_2 \rightarrow 2O + 4H_2$, and $C + CO_2 \rightarrow 2CO$, are promoted, so the production of H_2 and CO in syngas increases, while the production of CH_4 decreases. In the latter stage, with the increase of ER, too much O_2 is involved in the reaction, which promotes reactions $2CO + O_2 \rightarrow 2CO_2$ and $2H_2 + O_2 \rightarrow 2H_2O$, leading to the decrease of H_2 and CO production in syngas and the increase of CO_2 and H_2O production.

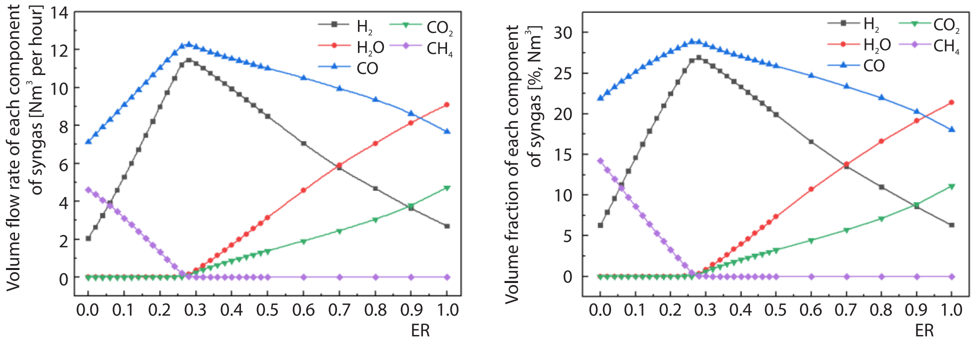

Figure 4. The effect of ER on syngas composition

As shown in fig. 5, the calorific value of syngas decreases with the increase of ER, but the calorific value of syngas increases when ER < 0.26. Subsequently, the calorific value of syngas begins to decrease due to the decrease of H_2 and CO output and the increase of CO_2 and H_2O output. The total calorific value of the syngas decreases due to the continuous heat release of reaction $2CH_4 + O_2 \rightarrow 2CO + 4H_2$, while when ER > 0.26, the calorific value decreases due to the decrease of CO and H_2 volume fractions in the syngas. The carbon conversion rate increases with the increase of ER because the remaining fixed carbon in the OBDC is oxidized with the increase of O_2. The carbon conversion rate tends to be stable when ER > 0.26. The gasification efficiency is positively correlated with the calorific value of syngas and increases slowly when ER < 0.26. When ER > 0.26, the efficiency of plasma gasification begins to decrease.

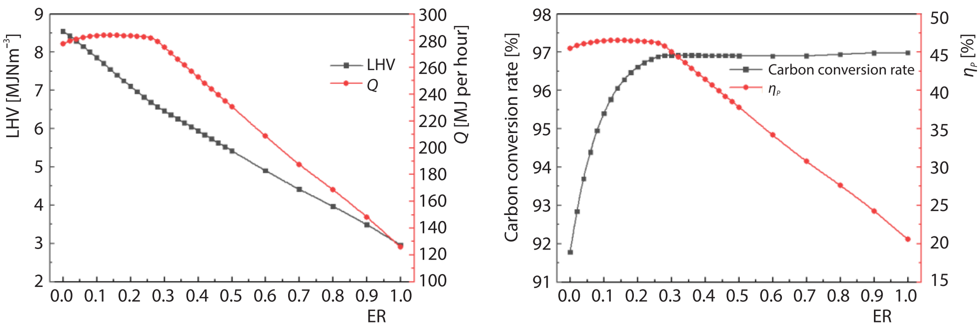

Figure 5. Influence of ER on gasification effect

Effect of moisture content on gasification results

The moisture content of OBDC has a great influence on the gasification result. To study the effect of it the gasification results, the simulation conditions are set the feeding rate for OBDC is 50 kg per hour, the temperature is 25 °C, the pressure is 1 bar, ER = 0.2, the output power of the plasma torch is 30 kW, and the moisture content varies from 3-20%.

The influence of water content on the volume fraction of each component of syngas is shown in fig. 6. It can be seen that CO_2 and H_2O in syngas begin to increase and CO and CH_4 begin to decrease when water content is 5%. The volume fraction of H_2 continues to increase when water content is less than 8% and tends to be stable when water content is greater than 8%. Water content has the greatest influence on the volume fraction of CO and CO_2 in syngas.

When the water content is less than 5%, water vapor participates in the reaction, and the yield of reaction $C + H_2O \rightarrow CO + H_2$, CO and H_2 begins to increase at high temperatures [19]. When the water content is more than 5%, the temperature field in the furnace will be affected and the water-gas conversion reaction $CO + H_2O \rightarrow CO_2 + H_2$ will be promoted at the same time.

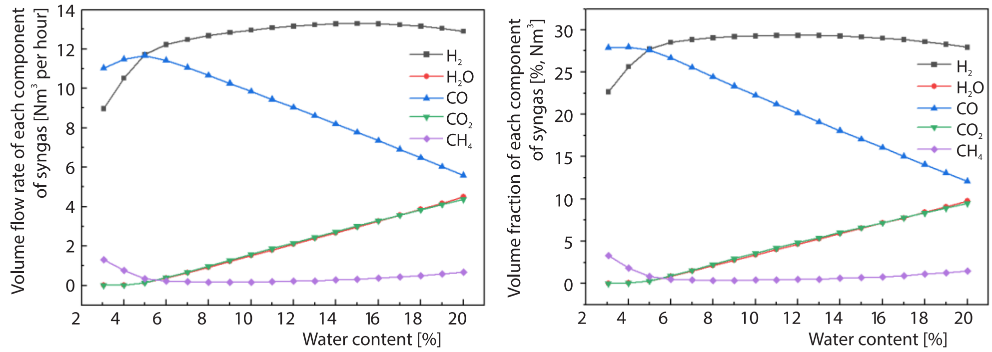

Figure 6. The effect of water content on syngas composition

As shown in fig. 7, the calorific value of syngas continues to decrease with the increase in moisture content. However, the total calorific value of syngas keeps increasing when the water content is less than 5% and decreases when the water content is more than 5%. The decrease in calorific value is due to the decrease in the proportion of combustible components of syngas due to the addition of water. When the water content is less than 5%, the efficiency of plasma gasification increases with the increase in water content. When the water content is more than 5%, the efficiency decreases gradually, and the changing trend is consistent with the changing trend of calorific value, while the carbon conversion remains unchanged.

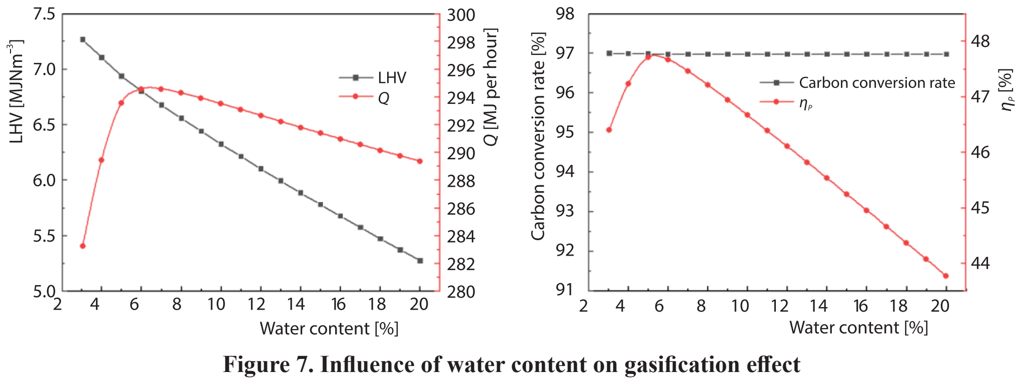

Figure 7. Influence of water content on gasification effect

Effect of the amount of CO_2 added on gasification results

Different gasification agents have a great influence on the gasification results of OBDC. A suitable gasification agent can improve the gasification efficiency of OBDC. To study the effect of CO_2 on OBDC gasification results, the simulated conditions are set the feeding rate for OBDC is 50 kg per hour, the temperature is 25 °C, the pressure is 1 bar, ER = 0, the output power of the plasma torch is 30 kW, and the amount of CO_2 added varies from 0-18 kg per hour.

As shown in fig. 8, when the amount of CO_2 added is less than 6 kg per hour, the volume fractions of CO and H_2 increase significantly, while CH_4 shows a trend of decreasing first and then increasing. When the amount of CO_2 added is greater than 6 kg per hour, the volume fraction of CO increases slowly, the volume fraction of H_2 begins to decrease, and CH_4 tends to be stable. At this time, H_2O and CO_2 begin to appear in syngas. The reason for such a change in syngas composition is that when the amount of CO_2 added is less than 6 kg per hour, reactions $2C_nH_m + 2nCO_2 \rightarrow mH_2 + 4nCO$ and $CO_2 + C \rightarrow 2CO$ occur in the gasifier; when the amount of CO_2 added is greater than 6 kg per hour, a small amount of reaction $CO_2 + H_2 \rightarrow CO + H_2O$ occurs.

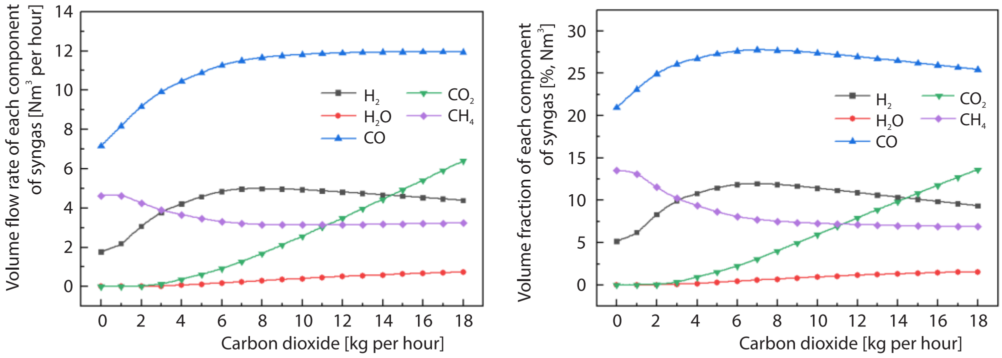

Figure 8. The effect of the amount of CO_2 added on syngas composition

As shown in fig. 9, the calorific value of syngas decreases continuously with the increase of CO_2 addition, but the number of carbon atoms in the combustible component of syngas increases due to the addition of CO_2, so the total calorific value of syngas keeps increasing. However, with the increase in CO_2 addition, the total calorific value tends to be stable. After removing the number of carbon atoms in CO_2 into the furnace, the carbon conversion rate increases first and then decreases with the increase of CO_2 into the furnace. This is because CO_2 acts as an oxidant at the beginning of the reaction, accelerating the oxidation of carbon atoms in the raw material. Later, excessive CO_2 inhibits the participation of carbon atoms in the reaction in the feed, so the carbon conversion rate drops slowly and then stabilizes at around 96%. The variation trend of plasma gasification efficiency is consistent with the total calorific value of syngas [20].

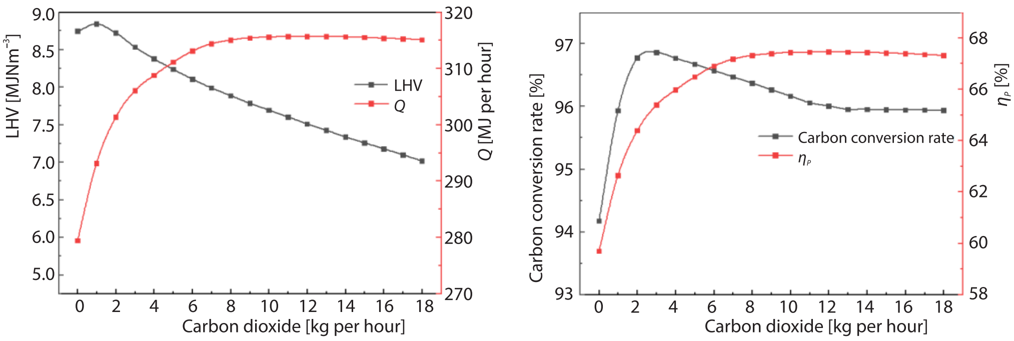

Figure 9. Influence of the amount of CO_2 added on gasification effect

Conclusion

The following conclusions can be obtained from the numerical simulation: the proportion of active component $CO + H_2$ in syngas increases as plasma torch output power, ER, water content, and CO_2 addition increase. Considering the factors such as carbon conversion rate, calorific value, and gasification efficiency, appropriate parameters should be selected to achieve a balance between energy consumption and treatment effect. Therefore, the optimal theoretical input power of this model should be 27.5 kW, ER = 0.26, water content is 5%, and CO_2 addition is 6 kg per hour. Because the gasifier in the actual experiment and industrial production process is not adiabatic, the input power of the plasma torch does not necessarily equal the output power, so the actual operation power should be greater than this value, and the specific numerical should be determined according to the specific situation of the equipment. This value is only for guidance and reference.

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