Preliminary Study of Thermal Treatment of Coke Wastewater Sludge Using Plasma Torch

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Abstract Thermal plasma was applied for the treatment of coke wastewater sludge derived from the steel industry in order to investigate the feasibility of the safe treatment and energy recovery of the sludge. A 30 kW plasma torch system was applied to study the vitrification and gas production of coke wastewater sludge. Toxicity leaching results indicated that the sludge treated via the thermal plasma process converted into a vitrified slag which resisted the leaching of heavy metals. CO_2 was utilized as working gas to study the production and heat energy of the syngas. The heating value of the gas products by thermal plasma achieved 8.43 kJ/L, indicating the further utilization of the gas products. Considering the utilization of the syngas and recovery heat from the gas products, the estimated treatment cost of coke wastewater sludge via plasma torch was about 0.98 CNY/kg sludge in the experiment. By preliminary economic analysis, the dehydration cost takes an important part of the total sludge treatment cost. The treatment cost of the coke wastewater sludge with 50 wt.% moisture was calculated to be about 1.45 CNY/kg sludge dry basis. The treatment cost of the coke wastewater sludge could be effectively controlled by decreasing the water content of the sludge. These findings suggest that an economic dewatering pretreatment method could be combined to cut the total treatment cost in an actual treatment process.

Keywords: thermal plasma, plasma torch, sludge, syngas, leachate toxicity

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(Some figures may appear in colour only in the online journal)

1 Introduction

The steel industry is one of the most important and vital industries in China, contributing to the rapid economy development and infrastructure that is currently exhibited in the country. According to the National Bureau of Statistics of the People's Republic of China (NBSC), the national crude steel production in China was about 822.69 Mt in 2014 [1], which dominates the world's total production of 49.25% [2]. Large volumes of sludge, slag and wastewater are produced as byproducts from the steel industry each year, which contain quantities of hazardous waste [3]. Coke wastewater sludge, a byproduct of the activated sludge process (ASP) for wastewater treatment of coke plant, contains toxic heavy metals and dangerous organic wastes, which may pose a serious problem to the environment if released without safely treated [4].

According to the regulation constituted by the Ministry of Environmental Protection of the People's Republic of China (MEPC), coke wastewater sludge is classified as a hazardous waste that needs to be safely treated to minimize the environmental threat. Major technologies that treat the sludge include landfilling and incineration. In China, most coke wastewater sludge is blended with coal for incineration. Fiscal subsidies are paid for the sludge incineration to compensate for the treatment cost. However, blended incineration may reduce oven temperature to a certain extent, which may also affect combustion efficiency and increase cost. Additionally, sludge incineration may give rise to potentially hazardous ash [4], which is required to be stabilized or immobilized for safe treatment [5]. While the Chinese economy and steel production continue to develop, conventional technologies will face stronger regulation restrictions [6].

In recent years, thermal plasma technology has been considered to be an attractive method to treat multiple types of hazardous wastes, including industrial sludge from wastewater treatment plants [7,8], bottom ash, fly ash [9,10], waste from municipal solid waste incineration [11,12], and medical waste [13]. This technology demonstrates a significantly lower environmental threat from exhaust gases and the leaching toxicity of slag waste than conventional methods, such as incineration [14,15]. Toxic organic compounds are decomposed effectively by thermal plasma. In addition, the vitrification process assisted with thermal plasma converts inorganic waste into non-leachable vitrified slag, in which non-violated hazardous wastes are immobilized [5,16]. However, there are few studies of coke wastewater sludge treatment via thermal plasma. Therefore, we investigate the toxicity leaching characteristics and the feasibility of using thermal plasma technology with coke wastewater sludge.

Coke wastewater sludge can be considered as an organic waste more than a hazardous waste. Researchers have mainly focused on the study of gas products and energy recovery when treating organic wastes or biomass by thermal pyrolysis/gasification assisted with plasma. Syngas (CO and H_2) is converted from organic waste decomposition by thermal plasma as the recovered energy [17,18]. Working gases of argon and nitrogen have been extensively used in the thermal plasma treatment of organic wastes [19]. Also, the composition of working gases has been studied to modify the composition of syngas produced. Conventionally, hydrogen, oxygen and steam are commonly mixed with working gas to promote syngas production. Ramachandran studied the thermal plasma in-flight treatment of electroplating sludge, by using argon as working gas, and compared it with different working gas compositions of Ar-H_2, Ar-N_2 and Ar-O_2 [7,8]. Tendler studied nitrogen plasma-based waste treatment and energy production through various wastes, and found the syngas volume fraction to be within the range of 53.8%–55.9%, and the gas composition of nitrogen to be within the range 35.1%–37.8% [20]. Tang used direct current (DC) arc nitrogen plasma to convert waste plastics into gaseous fuels, and with steam injection, he found the gaseous proportion of hydrogen and carbon monoxide to increase to 40% [21]. Shie studied the thermal pyrolysis of organic waste of rice straw using a nitrogen plasma torch, and found CO and H_2 to be the major components produced (excluding carrier gas N_2), and the mass yield of the syngas to increase on the addition of steam to the working gas [22]. Previous researchers have primarily utilized argon, nitrogen or mixtures of these inert gases as the working gas of thermal plasma. However, these inert gases also exited with the syngas after treatment. In recent years, the reaction mechanism of CO_2 in the thermal plasma atmosphere has been investigated [23,24]. The decomposition of CO_2 may modify the syngas composition, providing a theoretical basis for thermal plasma treatment and syngas energy recovery with CO_2. In this experiment, the feasibility of the thermal plasma treatment of coke wastewater sludge was studied. In addition, CO_2 was considered as a working gas to maximize syngas production and avoid inert gases in the gas composition.

A laboratory-scale plasma torch with 30 kW power capacities was applied. The experiment was conducted to examine the vitrification effect of heavy metals and gas production by thermal plasma. Carbon dioxide was used as the working gas to increase the syngas production rate. Preliminary economic analysis was carried out to evaluate the economic efficiency.

2 Methodology

2.1 Materials

The coke wastewater sludge used in this study was the ASP sludge of coke-making process derived from Wuhan Iron and Steel (Group) Corporation (WISCO), which is located in Wuhan, Hubei Province, central China. The sludge sample was pretreated and dewatered using a frame filter press at 8 MPa pressure for 40 min and dried for 7 days to dehydrate the surface water. Sludge samples were exposed in a blast drying cabinet at 105 °C for 24 hours, and the sample was pulverized and sieved into 40 mesh before use.

2.2 Apparatus and procedures

The experimental system consisted of a DC power supply, a plasma torch, a thermal reactor and a cooling system. The laboratory-scale apparatus used for the thermal plasma treatment of the coke wastewater sludge are shown in Fig. 1.

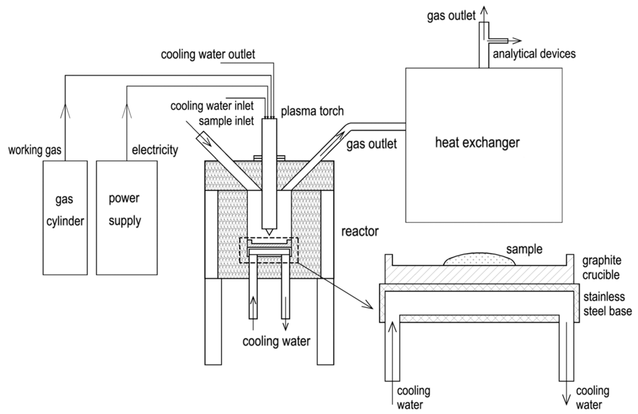

Fig.1 Schematic diagram of the plasma torch system

A 30 kW plasma torch was used for the treatment process. The power supply of the plasma torch could be controlled within the range of 6.5 kW to 26.3 kW for a corresponding current range of 40 A to 160 A. Due to the high temperature of thermal plasma ($T \geq 10^4$ K), the sludge exposed in thermal plasma decomposes rapidly, possibly into elementary constituents [25]. The energy input and energy density of the discharge increase with the current. Hence, a larger amount of sludge sample can be treated within certain time period, implying an increase in the treatment efficiency. However, the electrode ablates with an increase in the current, which shortens the electrode life. The balance between the treatment efficiency and the working life of the electrode is considered to prolong the electrode life. An effective current of 80 A was applied to treat the sludge sample until H_2 ceased to be detectable. The working gas CO_2 was controlled at a flow of 180 L/min at 273 K under atmospheric pressure.

The reactor was mainly constituted by a cylinder furnace with a cover made from an alumina refractory material. The thermally insulating 120-mm-thick alumina reduced the power loss to the furnace wall. The reactor had an external diameter of 350 mm and a height of 300 mm, an inner diameter of 110 mm and a hopper depth of 170 mm, which provide a capacity of approximate 1.6 L. A graphite crucible measuring 110 mm in diameter and 10 mm in thickness was placed on a stainless steel base, which contained a water cooling system at the bottom of the hopper. A schematic diagram of the graphite crucible and sample positioning is shown in Fig. 1. A commercial plasma torch, Zhengte 160, was applied as the cathode. The graphite crucible and the plasma torch acted as the anode and the cathode separately, which formed the transferred arc and plasma jet. The distance between the cathode and the anode was set as 7 mm. The sludge sample was placed in the graphite crucible. A 5 g sample was placed into the crucible per run of the experiment. The produced gas flowed into a spiral-plate heat exchanger surrounded by cooling water.

Gas products were detected and measured by analytical instruments at the outlet of the system. Gas products were detected using a KANE 940 flue gas analyzer, a Keernuo MT10519 methane analyzer, and a Keernuo GT901 hydrogen analyzer. The toxicity characteristics and leaching behavior of heavy metals (Pb, Cr, Cu, Cd) were analyzed using an AnalytikJenaAG AAS nov AA 400P atomic absorption spectrometer, according to the GB 5085.3-2007 hazardous wastes identification for extraction toxicity identification standards of MEPC. In addition, organic compound concentrations in the sludge were determined using an Agilent gas chromatography 7820 A; an HP-5 capillary column (length: 30 m, I.D.: 0.25 mm, film thickness: 0.25 μm) was applied to separate the organic compounds. The separation was attained via a temperature program using an injector temperature at 275 °C, at an initial oven temperature of 275 °C for 1 min, followed by incrementally ramping up the temperature by 310 °C at a rate of 10 °C·min^{-1}. Helium was used as the carrier gas. The elemental analysis for the coke wastewater sludge was performed using an Elementar Vario Micro elemental analyzer.

Commercial CO_2 was purchased from WISCO and was directly used without further purification. The gas standard employed was of 99.99% purity. Standard solutions of Pb, Cu, Cd, and Cr were purchased from the Institute for Environmental Reference Materials of MEPC.

3 Results and discussion

3.1 Characteristics of coke wastewater sludge

The proximate analysis, ultimate analysis, as well as higher heating value (HHV) of the sludge sample, are presented in Table 1.

Table 1. Analysis of coke wastewater sludge sample

Item	Value
Proximate analysis (wt.%)	
Fixed carbon	20.6
Volatile matter	65.4
Ash	12.7
Moisture	1.3
Ultimate analysis (wt.% dried)	
C	44.27
H	5.64
N	9.46
S	2.92
O	29.13
HHV (MJ/kg)	19.40

The results of the proximate analysis were 20.6 wt.%, 65.4 wt.%, 12.7 wt.%, 1.3 wt.% for fixed carbon, volatile matter, ash and moisture, respectively. The contents of C, H, N, S and O of the dry coke wastewater sludge were 44.27 wt.%, 5.64 wt.%, 9.46 wt.%, 2.92 wt.% and 29.13 wt.%, respectively (Table 1). The combustible value of coke wastewater sludge was 86 wt.% and the heating value was 19.40 MJ/kg, supporting the use of coke wastewater sludge as an energy source.

More than 70 organic compounds were detected in the coke wastewater sludge sample using a gas chromatography-mass spectrometer. The contents of polycyclic aromatic hydrocarbons (PAHs), benzene derivatives, esters and oxygen-containing heterocyclic compounds were 62.8%, 15.1%, 5.5% and 5.0%, respectively. The other constituents containing more than 1% were nitrogen-containing heterocyclic compounds, triophenes, halohydrocarbons, alkanes, benzonitriles and selenophens. In most organic compounds, the contents of benzo[e]fluoranthene, benzo[ghi]perylene, benzo[e]pyrene, triphenylene and phthalate of the dry coke wastewater sludge were 14.2%, 13.5%, 9.3%, 7.5% and 3.4%, respectively. Due to the carcinogenic and teratogenic effects of organic compounds, and their potential threat to the environment and human health, coke wastewater sludge is considered a hazardous waste that must be suitably treated.

3.2 Toxicity characteristic leaching results

Coke wastewater sludge was used in this investigation. Samples S_1, S_2, S_3 and S_4 were prepared using an addition of 5 wt.%, 10 wt.%, 15 wt.% and 20 wt.% SiO_2 in dry coke wastewater sludge, respectively. Samples S_{1a}, S_{2a}, S_{3a} and S_{4a} were prepared by adding concentration of 200 mg/kg of Pb, Cu, Cd and Cr on the basis of samples S_1, S_2, S_3 and S_4. Sample S_0 was the dry coke wastewater sludge. Samples S_1, S_2, S_3 and S_4, samples S_{1a}, S_{2a}, S_{3a} and S_{4a} were vitrified for 2 min by the plasma torch, while sample S_0 was pyrolyzed at 1100 °C for 60 min in the furnace.

Table 2. Characteristics of heavy metals in coke wastewater sludge and residue

Element	Pb	Cu	Cr	Cd
Concentrations (mg/kg)				
Coke wastewater sludge	93.6	50.3	113.2	10.9
Toxicity characteristic leaching results (mg/L)				
S_0	0.29	0.08	14.42	0.15
S_1	0.0011	0.019	0.0015	ND
S_2	ND	0.002	ND	ND
S_3	ND	ND	ND	ND
S_4	ND	ND	ND	ND
S_{1a}	0.0014	0.0357	0.0262	ND
S_{2a}	ND	0.0219	0.0077	ND
S_{3a}	ND	0.0053	0.0003	ND
S_{4a}	ND	0.0027	0.0003	ND
Limit value of MEPC	5	100	15	1
Leached fraction (wt.%)				
S_0	0.42	0.21	16.9	1.91
S_1	0.04	0.13	0.04	ND
S_2	ND	0.01	ND	ND
S_3	ND	ND	ND	ND
S_4	ND	ND	ND	ND
S_{1a}	0.05	0.10	0.06	ND
S_{2a}	ND	0.04	0.02	ND
S_{3a}	ND	0.02	0.01	ND
S_{4a}	ND	0.01	0.01	ND

Concentrations of heavy metals in the coke wastewater sludge are listed in Table 2. Modifications by increasing heavy metal contents of samples were made in order to further investigate the toxicity leaching characteristics. The toxicity leaching results of slags after treatment are listed in Table 2. The table shows that the heavy metal leaching concentrations of the residue after plasma vitrification were much below the regulation-limited value of MEPC. Comparatively, heavy metal leaching concentrations of residue by plasma vitrification were apparently less than by pyrolysis. The leached fraction of the sample by thermal plasma, which is the mass proportion of the leachate to the sludge sample, is obviously smaller than that of the sample treated by pyrolysis. SiO_2 took an important part in vitrification process, for the extracted amounts of heavy metals decreased as the SiO_2 content increased. Conclusively, coke wastewater sludge treated by the plasma torch with moderate SiO_2 additions can effectively prevent heavy metals from leaching.

3.3 Properties of gas products

No complex hydrocarbons were detected in gas products after thermal treatment by the plasma torch. This is similar to the findings that have been concluded in other studies [22,25,26]. Previous research has demonstrated that the chemical bond of CO_2 begins to crack at 1500 °C and can be thoroughly cracked above the temperature of 5000 °C [27]. Major gas product characteristics of the coke wastewater sludge via the plasma torch are presented in Table 3.

Table 3. Gas product characteristics of sludge sample treated via plasma torch

Gas product	CO	H_2	CO_2	O_2
Gas products yield (L/kg)	1798.8	487.1	446.7	706.1
Volume fraction (%)	52.3	14.2	13.0	20.5
Heating value (kJ/L)		8.43		
Heating value ratio (MJ/kg)		29.10		

According to Table 3, syngas volume fraction was about 66.5%. The volume fractions of CO and H_2 were 52.3% and 14.2%, separately. O_2 was measured in gas products as the product of CO_2 decomposition in thermal plasma. The disintegration of CO_2 provides additional CO along with the syngas derived from pyrolysis/gasification by thermal plasma. The oxygen derived from CO_2 disintegration may be useful for industrial applications. The mechanism of CO_2 reacting with electron initiating the plasma reaction has been studied by former researches [27,28]. It can be mainly proposed into two kinds of reactions, as given below.

a. Direct reaction with electron producing CO and O_2:

$$CO_2 + e \rightarrow CO + O + e \quad (1)$$

$$CO_2 + e \rightarrow C^+ + O_2 + 2e \quad (2)$$

b. Intermediate reaction producing CO and O_2 induced by radical intermediate species and ions like O, O_2^+, CO^+:

$$O + O_3 + M \rightarrow 2O_2 + M \quad (3)$$

$$O + O_3 \rightarrow 2O_2 \quad (4)$$

$$O_2^+ + CO_2 + e \rightarrow CO_2 + O_2 \quad (5)$$

$$CO^+ + O \rightarrow CO + O^+ \quad (6)$$

$$CO^+ + CO_2 \rightarrow CO + CO_2^+ \quad (7)$$

Considering the working gas of CO_2 and the dissociation of CO_2 in the thermal plasma process, higher-yield combustible gases can be achieved in the plasma torch system in order to gain higher heating value. The electric energy converted from the plasma torch to the thermal plasma, then transferred into sludge and finally stored in the syngas. The heating value of gas products by the thermal plasma process achieved 8.43 kJ/L, indicating that the further utilization of gas products is possible and valuable. By the thermal plasma treatment, the heating ratio of the coke wastewater sludge sample reached 29.10 MJ/kg. This indicates that the utilization of coke wastewater sludge and the heating value recycled from the sludge can be an effective method.

3.4 Energy and preliminary economic analysis

3.4.1 Energy consumption and recovery

Gas products and their corresponding energies in terms of heating values are induced by thermal plasma. The energy consumed per 1 kg of dry coke wastewater sludge treated with 10 wt.% of SiO_2 by thermal plasma, according to the aforementioned experimental results, is discussed below.

The heating value of coke wastewater sludge sample measured by adiabatic bomb calorimeter (19.42 MJ/kg) was close to the theoretical heating value of 18.38 MJ/kg calculated by Dulong formula. Thus, the Dulong formula [29] can be used to estimate the heating value in the experiment and is described as follows.

$$\mathrm{HHV} = 33.930\mathrm{C} + 114.32 \times (\mathrm{H} - 0.125\mathrm{O}) + 9.300\mathrm{S} + 1.494\mathrm{N}, \qquad (8)$$

where C, O, H, S and N represent the mass contents of elements in the sludge sample (%), which are listed in Table 1.

The heat energy input and consumption in the plasma torch system in the experiment are presented in Fig. 2.

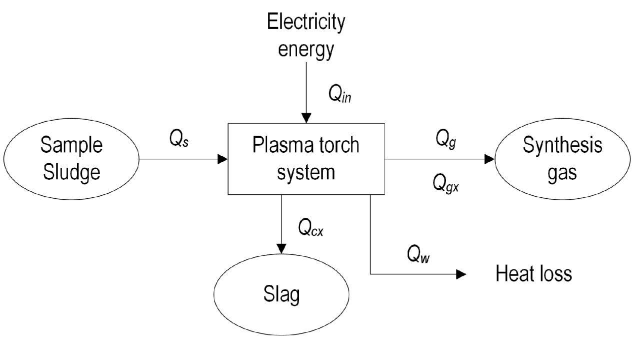

Fig.2 Block diagram of the plasma torch energy system

By preliminary analysis, the heating value of the sample sludge Q_s was 18.37 MJ/kg, which is lower heating value calculated from HHV. The energy input of the thermal plasma system, measured and calculated in terms of electricity Q_{in}, was 15.84 MJ. The heating value of gas products Q_g was 29.10 MJ, which is calculated in Table 3. Sensible heats of gas products Q_{gx} and residue slag Q_{cx}, which represent the heat value exchange when temperature varies, were calculated by Eqs. (9) and (10) [30], respectively.

$$Q_{gx} = V_g \sum (T_1 \cdot C_{p,i,T_1} - T_0 \cdot C_{p,i,T_0}) \cdot C_i, \qquad (9)$$

where T_0 is the room temperature, 25 °C; T_1 is the measured gas temperature from the reactor, 500 °C; V_g is the gas volume; C_i is the volume fraction of gas i in the gas mixture; and C_{p,i,T_1}, C_{p,i,T_0} are the mean specific heats of gas i at a certain temperature.

$$Q_{cx} = m_c \cdot C_{pc} \cdot (T_2 - T_0), \qquad (10)$$

where T_0 is the room temperature, 25 °C; T_2 is the estimated temperature of the solid residue, 1100 °C; m_c is the mass of the solid residue in the experiment; and C_{pc} is the mean specific heat of the vitrified solid residue, which is considered as a miscellaneous glass compound.

The sensible heat value of the gas products Q_{gx} was calculated as 2.35 MJ by Eq. (9), and that of the slag Q_{cx} was calculated as 191.6 kJ by Eq. (10). However, the high-temperature gas products can be cooled by water. The heat energy can be recovered by various heat exchangers in an industrial application. The gas products were cooled to room temperature by using a spiral-plate heat exchanger in the experiment. Recovering heat can be calculated from sensible heat Q_{gx} via a factor of recovery efficiency. Considering a heat recovery efficiency of 40%, the recovering of the heat energy by the heat exchanger Q_{re} was calculated as 941.3 KJ. The recovered energy heat can be applied to dry the coke wastewater sludge in order to reduce the water content. The energy recovery value R_g of the process was 0.85. Considering the heat energy recovery by the heat exchanger, the energy recovery value R_{all} of the process was approximately 0.88. The energy recovery values R_g and R_{all} can be estimated by employing the following formula [31].

$$R_g = \frac{Q_g}{Q_s + Q_{in}}, \qquad (11)$$

$$R_{all} = \frac{Q_g + Q_{re}}{Q_s + Q_{in}}, \qquad (12)$$

where R_g represents the energy recovery ratio of the thermal plasma process, and R_{all} represents the energy recovery ratio of the thermal plasma process and heat energy recycle process.

According to an actual application, the heat recovery in alternative method of electric heating can save 0.23 CNY/kg sludge when considering 0.9 CNY/kWh price of industrial electricity. Furthermore, the power consumed treating the dry sludge is 4.4 kWh and the cost of the thermal plasma treatment is 3.96 CNY/kg sludge. The utilization of the combustible gases offset the cost by 2.75 CNY/kg sludge when considering 0.8 CNY/m^3 of gas price in Wuhan. Therefore, the estimated treatment cost of the coke wastewater sludge sample via the plasma torch was about 0.98 CNY/kg sludge in this case.

3.4.2 Preliminary economic analysis

It is difficult and expensive to achieve the complete dehydration of sludge in the actual industrial process. Therefore, dehydration cost needs to be considered as part of treatment cost when treating wet sludge with plasma torch. Because the aforementioned work is only a laboratory-scale process, it may not be suitable for the economic analysis for an industrial application. Therefore, a preliminary economic analysis has been presented here to analyze the application potential of the actual process. The economic cost has been preliminarily calculated to an application of wet sludge with varying moisture contents. Water heating and evaporation have been considered as dehydration process, however, steam addition with plasma pyrolysis/gasification has not been considered to simplify the calculation.

The energy consumption of moisture in the sludge can be summarized into three parts: (a) moisture of the liquid phase in the sludge heated from room temperature to the boiling point; (b) water in the liquid phase to the vapor phase at the boiling point; (c) water vapor heated from boiling point to reaction temperature, calculated by formula (13) [30].

$$Q = C_{\mathrm{l,H_2O}} \cdot m \cdot p \cdot (T_{\mathrm{b}} - T_0) + \Delta vapH_{\mathrm{m}} \cdot m \cdot p / M_{\mathrm{H_2O}} + m \cdot p \cdot (T_1 C_{\mathrm{g,H_2O},T_1} - T_{\mathrm{b}} C_{\mathrm{g,H_2O},T_{\mathrm{b}}}), \tag{13}$$

where T_0 is the room temperature, 25 °C; T_1 is measured temperature of gas temperature from the reactor, 500 °C; and T_{b} is the boiling point of water. $C_{\mathrm{l,H_2O}}$, $C_{\mathrm{g,H_2O},T_1}$, $C_{\mathrm{g,H_2O},T_{\mathrm{b}}}$ are the mean specific heats of liquid water and gaseous water at T_1 and T_{b}, respectively. $\Delta vapH_{\mathrm{m}}$ is the molar enthalpy of vaporization. m is the mass of sludge, p is the moisture content, $M_{\mathrm{H_2O}}$ is the molar mass of water.

In the preliminary analysis, the energy input was considered as electric energy consumption, while the energy output and recovery were considered as the utilization of syngas and recovery of gas product heat by using the heat exchanger assuming a heat recovery efficiency of 40%. The treatment costs of the coke wastewater sludge for different moisture contents are shown in Table 4.

The treatment cost of the coke wastewater sludge increased with the moisture content. The treatment cost decreased from 3.71 CNY/kg sludge dry basis for a moisture content of 85% to 1.45 CNY/kg sludge dry basis for a moisture content of 50%, which was almost a 60% reduction of treatment cost. This implies that the dehydration of the coke sludge is an important process within the treatment cost. The thermal plasma technology has the economic advantage of treating low-moisture-content coke wastewater sludge. Therefore, pretreatment of sludge dewatering is a necessary component for controlling the treatment cost in an industrial application. However, the dehydration by plasma of wet sludge presents a high cost. Economic dehydration pretreatment methods can be combined with thermal plasma treatment to improve the efficiency and economy of the industrial application.

4 Conclusion

In this study, a thermal plasma technology was used for the treatment of coke wastewater sludge derived from steel production. Inorganic components and heavy metals contained in the coke wastewater sludge were converted into a non-leachable vitrified slag, which minimized the hazardous leaching threat to the environment. Carbon monoxide and hydrogen were main gas products of the sludge decomposed via plasma torch. CO_2 was utilized as the working gas in thermal plasma, and decomposed to increase the syngas production. The heating value of the syngas achieved 8.43 kg/L. The estimated treatment cost of the coke wastewater sludge sample via plasma torch was about 0.98 CNY/kg sludge. By preliminary economic analyzing, the treatment cost of the coke wastewater sludge can be controlled by decreasing the water content of the sludge. This would allow the combination of economic dewatering pretreatment methods to lower the treatment cost in an actual industrial treatment process. The laboratory-scale data are useful for the rational design and application of thermal treatment of coke wastewater sludge via plasma torch.

Table 4. Treatment cost of sludge for various moisture contents

Moisture content (%)	Energy input		Energy output		Treatment cost (CNY/kg)
	Sludge dewatering (kJ/kg)	Electricity (CNY/kg)	Syngas (CNY/kg)	Heat recovery (CNY/kg)	
85	18274.5	8.57	2.80	2.06	3.71
80	12899.7	7.22	2.80	1.53	2.90
70	7524.8	5.88	2.80	0.99	2.09
60	4837.4	5.21	2.80	0.71	1.69
50	3224.9	4.81	2.80	0.56	1.45

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