A Study on Direct Current Arc Plasma Torch Design with Preserve Nozzle for Perfluorinated Compounds (PFCs) Decomposition in Cement Kiln

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ABSTRACT

Perfluorinated compounds (PFCs), including sulfur hexafluoride (SF_6), are used as insulating gases for heavy electric equipment, and are greenhouse gases with a very high global warming potential. For the thermal decomposition of greenhouse gases, a high temperature of 3,000 K or more and a technology to prevent recombination of the decomposed gases are required. A direct current plasma arc with a flame temperature of 6,000 K or higher provides an effective ultra-high temperature for the decomposition of chemically stable PFCs. A large amount of CaO , which is a raw material for clinker, is in the cement kiln, hence the S and F radicals decomposed from SF_6 react with CaO to quickly convert it to CaF_2 and CaSO_4 and prevent their recombination. Therefore, the convergence technology of plasma and cement kiln is known as an effective method for treating PFCs. However, the interior of the cement kiln causes erosion of the plasma torch due to the turbulent flow of a large amount of combustion air at a high temperature of 1,500 °C or more, and the scattering of the raw material particles of the clinker, which greatly affects the operation stability. In this study, a plasma torch was developed that can maintain stable plasma in a vulnerable environment and effectively decompose PFCs. Moreover, the design and results of the experiment on the torch were presented to enable stable plasma operation for a long time in vulnerable environmental conditions through durability, plasma efficiency, and analysis of the discharge characteristics.

Keywords: Plasma torch, Perfluorinated compounds, SF_6 , Cement kiln

1. Introduction

Perfluorocompounds (PFCs), which are used as semiconductor process gases and insulating gases for power devices such as transformers, have a very long period of decomposition in the air. They are also known as representative greenhouse gases with a global warming potential (GWP) that is thousands to tens of thousands of times higher than that of CO_2 [1,2]. Reducing greenhouse gases to mitigate global warming is the most urgent task of the international community. Moreover, unlike the Kyoto Protocol, which obligates only developed countries to reduce greenhouse gases, the 21st Paris Convention on Climate Change (COP21) in 2015 imposed such an obligation on all 195 parties involved in the convention. Further international efforts have been made to preserve the global environment, with the 17 Sustainable Development Goals laid out at the Climate Change Conference in Madrid, Spain, in December 2019 to implement the 2015 Paris Agreement [3,4]. However, despite these regulations, PFCs are still gradually increasing with industrial development due to their inertness, nonflammability, and nontoxicity [5]. The US Environmental Protection Agency predicted that global fluorine-based gas emissions will gradually increase and reach 15.157 billion tons by 2030 [6]. In addition, according to the Republic of Korea's 2019 National Greenhouse Gas Inventory Report, the country's CO_2 emissions have increased 2.6 times since the 1990s, its SF_6 emissions have increased 38 times, and its PFC emissions have explosively increased 7700 times. The GWP of PFCs is very high compared to that of CO_2 [7]. As for SF_6 , its lifetime

Table I. Global warming potential and lifetime of major greenhouse gases.

Greenhouse gases	Lifetime (year)	Global warming potential
CO_2	50–200	1
CF_4	50,000	6,500
CHF_3	250–390	11,700
NF_3	50–740	8,000
CH_4	12	21
SF_6	3,200	23,900

is about 3,200 years, its GWP is 23,900, and it is predicted to continuously contribute to increased global warming. Table I shows the lifetime and the GWP of representative PFCs [8].

Clearly, effective treatment of such greenhouse gases is urgently needed. Technologies such as a separation and recovery method through chemical adsorption, a catalyst method, and a decomposition and removal method using a combustion method have been studied for many years [9–13]. However, these methods have problems such as high treatment cost, low throughput, and generation of secondary pollutants such as side reactants and liquid wastewater. In particular, decomposed gases are not recognized as high-capacity processing technology because of the problem of reduced processing efficiency as they are recombined. Meanwhile, the PFC treatment technology that combines high-temperature plasma and a cement kiln can be as an effective method for overcoming these shortcomings. In the high-temperature

plasma, the temperature of the plasma jet is 6,000 K or higher, hence a high-temperature environment can be created that can sufficiently decompose PFCs. A large amount of CaO, a raw material of clinker, exists in the cement kiln at a temperature above 1,500 °C and reacts chemically with the decomposed S and F components until they are converted into CaF₂ and CaSO₄, thereby preventing their recombination and achieving high processing efficiency [14]. However, the internal environment of the cement kiln is problematic due to high temperatures and very strong turbulence caused by high levels of anthracite combustion gases, dust generated from clinker raw materials, and the HF generated during the conversion of CaF₂ and CaSO₄, resulting in unstable discharge or shorter electrode replacement cycles. Therefore, a torch design must be developed that can secure the stability of the application of the plasma torch to the cement kiln. In this study, to effectively treat a large amount of PFCs, a triple-designed plasma torch was developed that can be installed in a cement kiln and used for a long time. The developed plasma torch was installed in a cement kiln, and the discharge was evaluated. An experiment to predict the lifespan was carried out. To secure the stability of the plasma torch, a preserve nozzle was installed at the end of the anode nozzle that prevented foreign substances from entering the plasma nozzle, thereby effectively stopping the erosion of the nozzle. The PFC was supplied to the center of the plasma torch and mixed with the air current of the plasma jet generated from the triple torch to achieve effective decomposition. Nitrogen was used as the plasma discharge gas so that its rotation and supply would prevent the bias of the plasma arcs. Nitrogen also mediated heat transfer to the PFC, which was injected simultaneously, enabling an effective decomposition reaction for low-power operations. A protective metal cover was installed on the exterior of the plasma torch, which also prevented electrical hazards to the cathode and anode power cables. By developing plasma torch design, this study presented a plasma torch that can be used for a long time to stably generate and maintain plasma in various industries without being affected by the surrounding environment.

2. Experimental details

Figure 1 shows the design drawings and the manufactured photos for the design of the triple thermal plasma torch developed in this study. The internal design of the plasma torch consisted of a cathode made of tungsten and an anode made of copper. The anode was connected to the outer housing, and the inside of the housing was filled with an insulating material made of polymer. Each plasma torch was integrated with a support composed of the front and back, and the PFC came out to the center where three plasma jets were ejected and decomposed through contact with the plasma. The plasma jet was ejected at speeds of more than 400 m/s at a reduced gas density due to high temperatures of about 6,000 K. At this time, local pressure differences around the plasma torch decompose foreign substances such as crinker dust and non-ferrous coal around the nozzle, and HF gener-

Figure 1. (a) 2D cross-sectional view of the nozzle part of the torch with or without the preserve nozzle. (b) 3D modeling of the triple plasma torch. (c) Triple plasma torch manufactured by the design drawing.

Figure 2. Schematic diagram of DC plasma torch system and cement kiln for PFCs treatment.

ated during conversion to CaF₂ and CaSO₄ enters the anode nozzle, causing erosion and acceleration of the anode nozzle. To prevent foreign substances from entering the anode nozzle, preserve nozzles were applied to the tip of the anode nozzle, as shown in Fig. 1. The preserve nozzle materials require high heat resistance to withstand high plasma temperatures; and as tungsten has a high strength and a melting point of 3,400 °C, it is the most heat-resistant metal in existence, but it is easily damaged by hot-shortness. Therefore, molybdenum was used as its replacement metal [15–17]. The melting point of molybdenum is 2,610 °C, and it is known to have high heat and corrosion resistance. The plasma torches developed in this study were mounted on cement kilns to treat the PFC and evaluate the operation. Figure 2 shows a schematic diagram of the cement kiln and plasma torch systems used in this experiment. The cement kiln used was the No. 6 Kiln of Sungshin Cement Co., Ltd., located in Maepo, Danyang, Chungcheongbuk-do. The waste gas used was the PFCs recovered from waste transformers. The plasma power system (PS20, Dawonsys) was operated at an output of 20 kW, and the dischargers supplied 100 L/min of nitrogen gas per torch. To observe the voltage–current/discharge characteristics of the plasma, an oscilloscope (DPO 4054, Tektronix), current probes (TCP-404XL, Tektronix), and voltage probes (DP-50 and PIN-TEK) were connected to the torch. To calculate the thermal efficiency calculation of the plasma torches, the flow rate of the cooling water supplied to the torches was measured, as were the temperatures of the cooling water inlet and outlet. The thermal efficiency of the plasma torches was calculated using the equation,

$$\eta(\%) = \frac{P_{IN} - [C_{pw} \dot{m}(T_{OUT} - T_{IN})]}{P_{IN}} \times 100 \quad (1)$$

where P_{IN} is the plasma input power (J/s), and T_{OUT} and T_{IN} are the outlet and inlet temperatures (K) of the plasma torch coolant. C_{pw} is the heat capacity (J/g · K) of the cooling water, and $\dot{m}$ is the cooling water mass flow rate (g/s).

3. Results and discussion

Figure 3 shows the current and voltage waveforms measured for 1 h using the oscilloscope after the plasma torch installed in the cement kiln was discharged. The average voltage was 200 V and the average current was maintained at 100 A. In the DC arc plasma, a fluctuating voltage was generated and appeared as a voltage fluctuation range because of restrike; as the arc moved along the inner surface of the electrode, the voltage increased along with an increase in resistance, and re-discharge occurred at the shortest distance of the electrode. The intensity of the oscillation voltage increased with time and accelerated electrode erosion [18]. The torch developed in this study seems to generate restrike even with a preserve nozzle. Thus, a stable discharge is maintained. As a result, the plasma torch lifetime can be extended. Figure 4 shows the voltage characteristics according to the discharge gas flow rate for the torch to which the preserve nozzle was applied and the torch to which it was not applied. The voltage of the torch to which the preserved torch was applied appeared to have risen by 2–4 V according to the flow conditions of the discharge gas, compared to

Figure 3. Voltage and current waveforms of during DC arc discharge. (a) Plasma output voltage. (b) Plasma current.

the non-preserved torch. This result can be attributed to the increase in the length of the anode nozzle after the application of the preserve nozzle. Compared to the torch to which the preserve nozzle was not applied, the flow rate of the discharge gas of the torch increased by 2 – 4 V. This is due to the increase in the length of the anode nozzle after the application of the preserve nozzle. As the length of the anode nozzle increased, the force with which the discharge gas repelled the arc also increased. When the arc pushing force increased, the arc became longer, indicating that the resistance of the electric discharge gas increased. Therefore, application of the preserve nozzle can increase the plasma output. Figure 5 shows the erosion and weight reduction of the preserve nozzle and anode nozzle with time, depending on the presence or absence of preserve nozzles operating in cement kilns. Torches without a preserve nozzle under an operating voltage of 200 V, current of 100 A, and discharge of 100 L/min become difficult to use after 300 h of operation owing to corrosion of the anode nozzle. However, those with a preserve nozzle have a relatively good initial form, even after 1,000 h of use. In addition, after 1,000 h of operation, the weight losses of the anode and preserve nozzle were 3.59 and 6.4 g, respectively, resulting in 2.9 and 13.8% weight losses due to erosion compared with the initial conditions. Additional use is available in terms of weight loss only. The preserve nozzle adhered

Figure 4. Voltage by flow rate of electric discharge gas depending on whether or not preserve nozzle is applied.

Figure 5. The erosion and weight reduction of the nozzle according to plasma operation time. (a) The erosion of the anode nozzle of the torch after 300 h without the preserve nozzle. (b) The erosion condition and weight reduction of the positive and preserve nozzle of the torch applied with preserve nozzle according to the operation time. (c) Initial surface condition of the preserve nozzle and condition after 1,000 h of operation.

to the anode nozzle, and plasma jets discharged from the end of the anode nozzle were released outward through the preserve nozzle. As the inner surface of the preserve nozzle was in direct contact with the high-temperature plasma and the outside surface was exposed to the cement kiln, deformation was caused by collision with external foreign substances along with the high temperature. Meanwhile, the surface of the anode nozzle was confirmed to have been clean. As the diameter grew at the end of the anode nozzle, a certain degree of erosion occurred, which is believed to have been caused by the accumulated surface sputtering of the arcs. This study confirmed that the torch with the preserve nozzle can be used for more than 1,000 h. Moreover, considering that the replacement cycle of the semiconductor waste gas treatment plasma torch was around 500 h, this experimental result is remarkable in terms of improvement to the durability of the plasma torch. The thermal efficiency was calculated by measuring the inlet and outlet temperatures of the coolant during the plasma operation. Under 20 kW plasma operating conditions, the flow rate of coolant was 10 L/min, and the temperature difference between the inlet and outlet was only 6 °C, respectively. Using Eq. (1), the thermal efficiency of the plasma torch developed in this study was found to be high (79.1%). The efficiency of plasma torches for decomposition of PFCs used in semiconductor scrubbers is usually 60 to 65%, but the efficiency of plasma torches developed in this study was found to be more than 14%. High plasma efficiency means that the thermal energy contributing to the decomposition of PFCs is high, which can result in higher decomposition efficiency.

4. Conclusions

Recently, technologies that can reliably process large volumes of gases—such as PCFs (including SF₆ gas)—with a very high GWP have received considerable attention because of growing interest in the global environment. In this study, high-temperature plasma and a cement kiln were used for large-capacity greenhouse gas treatment. First, a plasma torch was designed for reliable use in the cement kiln. Second, the discharge characteristics, thermal efficiency, and durability of the plasma torch were analyzed. Continuous operation of the plasma torch for more than 1,000 h while maintaining the plasma characteristics even in environments with a high temperature, vibration, and strong turbulent flow was verified using a molybdenum preserve nozzle. At this time, the plasma efficiency was measured as 79.1%, confirming the superior durability and efficiency of the developed plasma torch to those of the conventional PFC treatment torch. These results show that the high-temperature plasma torch can be considered advanced technology with high utility in various waste gas treatment processes and plasma incineration fields by overcoming the short lifespan due to electrode erosion, which is a known disadvantage of high-temperature plasma torches.

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Conflict of Interest

The authors declare no conflicts of interest.

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