

Chapter 2

Non-thermal Arc Plasma for Ethanol Reforming and Hydrogen Production

2.1 Non-thermal Plasma

Non-thermal plasma, also called non equilibrium arc plasma, is a kind of low temperature plasma. Thermal arc plasma is usually driven by a high power supply and characterized by a high current (several amperes to tens of amperes) and a small low voltage (tens of voltage). It is a kind of strongly self-sustaining high-temperature discharge. Unlike thermal plasma, non-thermal arc plasma is usually driven by a low AC or DC power supply and characterized by a high voltage (several thousand voltages) and a small low current (tens to hundreds amperes). Non-thermal plasma can generally be divided into non-thermal fixed arc plasma and non-thermal free arc plasma, and non-thermal free arc plasma can be divided into knife-shaped electrodes non-thermal plasma, semi-free rotated arc discharge and free rotated arc discharge. In the last section, various non-thermal arc ethanol reforming systems are introduced.

Non-thermal fixed plasma can be generated by a pair of opposite tip electrodes or rod-shaped electrodes [1, 2]. For the reforming of liquid fuel, the most used reforming process and oxidation-steam reforming with this kind of discharge. There are two ways to feed the materials: (1) the pair of electrodes are immersed in the liquid phase, and two flows of air are input along the axis of the pair of electrodes and then a stable countercurrent gas passage can be generated in the electrode gaps; (2) an air flow is introduced to the discharge zone from the center bore of an electrode [1, 2]. Due to the fact that the direction of the air flow and that of the arc are the same, the position and the length is relatively fixed. This kind of discharge is also called non-thermal fixed arc discharge.

Knife-shaped gliding arc plasma is one of the simplest non-thermal free arc discharges, with the characteristics of high power and high non equilibrium. Hence, this kind of discharge is widely used in the preparation of materials [3], treatment of pollutants [4, 5], disinfection [6, 7] and fuel reforming [8]. A pair of this kind of discharge reactors is made up of a pair of coplanar opposite knife-shaped metal

sheets. When applying a high voltage, an arc is generated at the smallest gap between the electrodes. Then the arc slides towards the direction to which the electrodes gradually increase, and therefore the arc grows more and more curved. As the arc grows, when the energy loss is lower than the input energy, the gas temperature decreases while the temperature of the electrons is still very high. At this time, free arc thermal plasma transfers to non-thermal plasma. When the arc increases till the length is too large, the applied voltage continues to supply the energy needed for sustaining it, and then the conductivity of the plasma channel plummets, leading to the quenching of the plasma. At the same time, a new arc is generated in the smallest gap between the electrodes. The processes mentioned above circulate continually and discharge is sustained.

Five knife-shaped gliding arcs with different sizes were utilized for diethyl ether reforming [8]. It was found that the size of the discharge zone and the reforming efficiency increased with an effective electrode length and/or a slope radius of the downstream region of the electrodes. Some researchers have also used three sheets of knife-shaped electrodes or the simplified bent rod electrode for the treatment of methane and tetrafluoroethane [9, 10].

Semi-free rotating arc discharge and free discharge both use a coaxial hollow external electrode and a center electrode, their external electrode is columnar, trumpet-shaped or zoom tube-shaped, while the center electrode is rod-shaped [11–13]. In the semi-free rotation arc discharge, the center electrode is positioned outside the external electrode. When both ends of the electrodes produce an electrical breakdown, one end of the arc root is fixed to the center electrode, the other end wanders on the external electrode under the effect of a gas flow and/or a magnetic field. In the free rotation arc discharge, the center electrode covers the entire external electrodes, so both ends of the arc can move freely on the two electrodes under the effect of an airflow and/or a magnetic field. In order to ensure the full connection and the reaction between the plasma and the feed stream in the discharge area, the tangential feed method is generally used to produce a rotating air flow. The above two types of discharge have been used in areas such as the degradation of toluene and NH_3 , the reforming of methane to produce hydrogen and the synthesis of TiO_2 nanopowder and so on [14–18].

Zoom electrode freedom arc discharge plasma is a kind of special free rotation arc discharge. The reactor has the appearance of a long cylinder, and its electrode is made up of the coaxial center electrode and the zoom tube external electrode, the center electrode is a thin metal rod and the external electrode is a metal convergent-divergent nozzle. The center electrode covers the whole nozzle, so the narrowest point of the nozzle is also the point between the electrodes that has the smallest gap. There are a number of tangential inlet holes on the top of the reactor to make the feed stream mix fully and form a cyclone in front of the discharge area. When the cyclone flows towards the downstream along the zoom, its flow rate increases rapidly while it maintains the rotation, and the air pressure decreases.

Electrical breakdown occurs to this cyclone at the narrowest point of the nozzle after AC high voltage is applied to the electrodes, and then the arc rotates and stretches with the cyclone downstream until it quenches.

2.2 Non-thermal Arc Plasma Reforming of Ethanol to Produce Hydrogen

A non-thermal fixed arc plasma was designed and the reforming effect of the ethanol solution was assessed through experiments and numerical simulation [19, 29]. In its discharge configuration, both of the electrodes were immersed in an ethanol solution and the two flows of air in opposite directions flowed along the two electrodes and the electrical breakdown and reforming occurred to the air flows and the solution in the gap of the electrode. The raw materials of the reforming were 50% ethanol solution and air, the flow rate of the air 38 cm³/s, the discharge current is 300 mA and the power was about 100 W. It was suggested that the content of the hydrogen in the gas produced reaches the highest level when the mole fraction of ethanol in the ethanol solution is 50%; at this time the conversion of ethanol and the yield of hydrogen are about 50 and 15% respectively. Concentrations of H₂ and CO are almost the same in the gas produced, and based on that, the author speculated that the temperature inside the reactor was about 355 K.

Another kind of non-thermal fixed arc plasma was used to reform the alcohols, bio-oil and wood [1]. The reactor was made up of a quartz envelope (the length was 400 mm, the internal diameter was 30 mm) and two graphite electrodes, the electrode gap was 10 mm. The apparent diameter of the arc column was 2 mm under the conditions of discharge. There was a through hole on the upper electrode axis, gasification of the ethanol solution happened before the ethanol solution entered the discharge region via the through hole, and the graphite electrodes were heated by the discharge in the reforming process. The main gaseous products detected in the experiment were H₂, CO, CO₂ and CH₄, and the volume fraction of C₂ was less than 1.5%.

One kind of non-thermal pulsed plasma sliding arc reactor with a spray nozzle was designed to explore the hydrogen generation rate and the energy efficiency when using methanol, ethanol and propanol as raw materials. A planar knife-shaped electrode configuration was used in the reactor. In the experiment, an alcohol solution was added into the reaction zone in the form of a pulse with Ar as a carrier so the temperature of the liquid in the reactor only increased by 1–2 °C. The production rate of hydrogen was 3.4–5.0 μmol/s when the discharge power was 0.45 W and 40% aerosol solution was added, of which the net volume of ethanol was 4–20 ml/min, and the energy consumption per hydrogen produced reached 90 kJ/mol_{H₂} at the maximum flow. It was also found in this study that the production rate of hydrogen would increase significantly with the increase in the flow rate of the feed stream and they speculated that this was because of the shorter

residence time and quicker quenching and therefore the radical reaction which would result in the transformation if the target product was limited. In addition, they also used this type of plasma to process a stream of water droplets, and obtained H_2 and H_2O_2 effectively at the low power of 0.3–0.45 W [20].

A reformer of semi-free arc plasma was proposed to produce hydrogen by the reforming of liquid fuels such as gasoline, heptane, ethanol and E85 and so on [11, 21–23]. The flow rate of the ethanol solution was set to 0.25 g/s and the discharge power was 1200 W in the experiment (Equivalent to 18% of the heating value of feedstock ethanol at a low temperature). The theoretical calculation and the result of the experiment both showed that the best reforming conditions are $O/C = 0.5$ and $S/C = 0.5$, at which the conversion of ethanol is 65%, the yield of hydrogen is 35% and the energy consumption of per hydrogen produced is 106–120 kJ/mol H_2 , while, when using E85 as the raw material, the above values become 90%, 65% and 60–100 kJ/mol H_2 under the condition of $O/C = 1.16$, $S/C = 0.2$. In addition, there was no carbon deposition on the device during the two-hour continuous operation, which shows that the device has a good stability [11].

A kind of convergent-divergent tube free arc discharge reactor was designed to explore the volt-ampere characteristic of this discharge and the reforming effect of bio-ethanol as the focus [13]. The external electrode of this reactor was a copper convergent-divergent nozzle (the length was 106 mm, the narrowest inside diameter was 10 mm), the central electrode was made up of a fine stainless steel column (the length was 300 mm, the diameter was 5 mm), so the narrowest distance between the two electrodes was 2.5 mm. The power used was generated from the transformation of the 220 V AC through the AC leakage transformer (50 Hz, 10 kV). There were four tangential inlet ports at the top of the reactor, one of which was equipped with a gas-liquid nozzle to gasify the ethanol solution and form a high-speed vortex flow. The major reformat was synthesis gas (H_2 and CO), and other by-products such as C_2H_2 , C_2H_4 , C_2H_6 , CO_2 , CH_4 and so on were also generated. Besides, the emission of nitrogen oxide in the reforming process was very low (<10 ppm). The experiment explored the effect of reforming of the bio-ethanol through reaction parameters such as the O/C ratio, the S/C ratio, the amount of ethanol and power and so on. A higher conversion rate of ethanol (90%) and a general yield of H_2 (40%) were obtained in the study and the best conditions for ethanol reforming were $S/C = 2.0$, and $O/C = 1.4$ –1.6. When the amount of ethanol added was 0.15 g/s, the O/C ratio was 1.4 and the S/C ratio was 2.0, energy consumption required to produce one unit of hydrogen was 72.92 kJ/mol, reaching the minimum level. In the experiment, an oscilloscope and high-speed photography were also used to analyze the discharge characteristics of the converging-diverging electrode arc discharge reactor and it was found that an increase in the air flow will result in an increase in the instability of the change of the voltage and the current and the arc wire would appear split under the high airflow, which could improve the reforming efficiency of ethanol to a certain degree. The above findings indicate that this reforming process has an underestimated potential in the field of renewable energy.

2.3 Factors Affecting on Plasma Reforming of Ethanol

Various factors will affect the results of the reforming in the reactions of plasma in reforming ethanol. For example, the steam reforming reaction of water and ethanol will have different reaction processes when adding different proportions of water into the reaction of alcohol reforming. H and OH radicals generated by water in the plasma discharge will help the decomposition of ethanol. In addition, oxygen in the air can be ionized O radicals in the discharge when using air as the carrier gas. Next we will discuss the important factors that affect alcohol reforming.

2.3.1 *Effects of the Components of the Materials*

The components of the raw materials play an important role in the generation of free radicals, thus affecting the efficiency of the reforming and the distribution of the product. O–H bond energy of H_2O is 497.1 kJ/mol, while C–H bond energy of the methanol molecule is 95.18 kJ/mol, so the reaction activity of methanol in the plasma is higher than water [24]. Reactive components such as hydrogen atoms and hydrogen radicals and so on can be generated by the dehydrogenation reaction of H_2O molecules under the effect of the plasma. A DFT study on the corona discharge methanol reforming was conducted, and it was found that the decomposition of water can promote the generation of CH_2OH when it exists, which is because the OH radicals that are generated from the decomposition of water molecules can cause the oxidation decomposition of methanol [25]. The maximum yield of hydrogen can be produced when there is an appropriate amount of hydrogen in the raw materials; one of the reasons is that O is generated in the decomposition of water in the process of the partial oxidation reforming of alcohols, thereby increasing the production of hydrogen. In addition, H atoms produced during the decomposition of water can combine with each other and generate hydrogen. Take methanol for example: the amount of OH radicals will decrease with an increase in the concentration of methanol, causing the production of acid and CO_2 . The relationship between the O/C ratio, the S/C ratio and the reforming efficiency was studied, and it was beneficial for the degradation of ethanol and the generation of H_2 and with an increase in the content of oxygen in the carrier gas, the conversion of ethanol showed a trend in which it first increased and then slowed down [26]. When the content of water increases, O radicals and H radicals generated from the water become more active, thereby promoting the ethanol molecule to participate in the collision reaction and its degradation significantly. When the content of oxygen increases, oxygen-free radicals generated by the oxygen can combine with the free radicals that are produced by the decomposition of ethanol quickly and transform into hydrocarbons, finally resulting in the increase in the conversion rate of ethanol. The experiments were conducted to study the effects on the reforming of different

amounts of ethanol and water, and the results showed that the reduction of the amount of water will result in the reduction of the yield of hydrogen and carbon dioxide and an increase in the yield of carbon monoxide [27].

2.3.2 *Effects of the Carrier Gas*

The carrier gas is closely linked with the types of the radicals that are generated in the alcohol reforming processes, so it can significantly affect the generation of gaseous products. Oxygen can degrade into oxygen free radicals with a high reactivity in the plasma discharge process to promote the oxidation decomposition of ethanol. Nitrogen in the air can also produce nitrogen oxides in the plasma discharge process, which has impacts on the environment. In the air plasma, oxygen and nitrogen will generate oxygen radicals and nitrogen radicals respectively under the impact of electrons. These two radicals can react and generate NO, NO can be converted to NO₂ under the role of oxygen free radicals, oxygen or ozone. Nitrogen needs 9.8 eV energy to dissociate up to N radicals and the energy that the oxygen needs to dissociate up to oxygen radicals is 6 eV, thus it will help to control the production of nitrogen oxides by controlling the reaction conditions, especially the discharge power. In addition, as a cheap industrial gas, argon gas is often used as a carrier gas in the plasma system. Argon will not affect the chemical reaction as the carrier gas, but it will affect the electron energy distribution equation [28]. Although argon will produce Ar in the plasma discharge process, the rate of the reaction between Ar* and ethanol is lower than that of the reaction between the ethanol molecule and the electron. In addition, the reaction between Ar* and ethanol requires a certain amount of Ar* so this reaction is negligible [29]. The experiment of the glow discharge plasma reforming of ethanol was conducted, and the production of the CO₂ can be reduced effectively by using argon as the carrier gas [29]. In addition, the flow of argon will also have an impact on the reaction system. A decomposition experiment of microwave plasma ethanol was conducted, and the impacts of the flow of argon on the reforming reaction were analysed [30]. It was found that as the flow of argon rises from 0.5 L/min to 1.5 L/min, the temperature of the gas drops from 3700 to 2500 K. It was shown that the relationship between the yield of hydrogen and the carrier gas in the non-thermal plasma is as follows: Ar > N₂ > Air ≈ O₂ [31, 32]. The reasons are as follows: (1) compared with N₂($a^1\Pi_g$, 8.59 eV), Ar($1\Pi_1^0$, 11.83 eV) can transmit more energy to the methanol so a higher yield of hydrogen can be obtained in Ar; (2) electric dipole transitions from N₂($X^1\Sigma_g^+$) to N₂($a^1\Pi_g$) are limited, so the excited reaction of N₂ is slightly weaker than that of Ar; (3) as a background gas, O₂ and the effects of the air on promoting the reaction are weaker, O₂ can react with hydrogen radicals produced by water or H₂ rapidly and produce water.

2.3.3 *Effects of the Input Power*

It was found that the conversion of methane increases with the increase in power, and it has nothing to do with the frequency or change of the voltage; for the latter it was found that the energy and density of the electron is only closely related to the voltage, so the energy and density of the electrons could not be affected by adjusting the frequency to change the power [33, 34]. Our lab found that when the frequency is fixed, the size of the input power will affect the hydrogen production performance of the oxidation reforming of ethanol by affecting the conversion of ethanol and the yield of H_2 . An increase in the plasma power can improve the density of high-energy electrons, thereby strengthening the excitation reaction caused by the electron collision and promoting the conversion of the alcohol. There is an important relation between power and the density of the plasma and almost all the energy is transferred to the electrons in the non-thermal plasma. Under the condition of plasma, a large number of active ingredients (high energy electrons, free radicals and so on) generated in the electron-molecule degradation promotes the decomposition of alcohols. The energy density of the discharge region, the average energy and the number of high-energy electrons will increase with the increase in the input power. And the increase in the high-energy electrons has a positive effect on the small molecules such as hydrogen and so on. The thickness of the plasma sheath (i.e., the volume of the plasma) increases with an increase in the discharge power; this indicates that the reaction channels of the high-energy electron in the discharge plasma increase and that the probability that the collisions of the high-energy electrons lead to degradation of the fuel molecule will increase with the increase in the voltage. However, the voltage cannot increase indefinitely, and the discharge electrode will melt when the voltage increases to a certain value, so the effect of the reforming cannot be increased infinitely. It was also observed that the increase in voltage usually helps to improve the conversion rate of the alcohol. In order to further improve the rate of production, we should study the reforming mechanism of alcohol in a profound way, so that we can better control the process of plasma reforming [35].

2.3.4 *Effects of Other Factors*

Temperature can be used to indicate the energy level obtained in the excitation reaction of the radicals caused by the involvement in the plasma of the heavy particles in the plasma reaction [31]. Radical chemistry reaction is closely linked to the temperature, while the electron collision reaction and the electron adsorption are not very closely linked to the temperature [36]. Various unwanted byproducts such as acetaldehyde, acetone and ethylene will be produced when the reaction temperature is low in practice. The conversion of ethanol and the yield of hydrogen will increase when increasing the reaction temperature of the gas mixture, and

meanwhile, the selectivity of H_2 , CO , CO_2 and CH_4 will improve and the selectivity of acetaldehyde, acetone and ethylene will decrease [37]. Since the mixed gas in the post-reaction zone is still at a relatively high temperature, the conversion reaction still occurs effectively after the discharge quenches [38]. It is believed that the effect of high temperature is caused by the increase in the rate of the electron—molecule collision reaction [38]. It was found that the H_2/CO ratio will increase and the concentration of the hydrocarbon will decrease with an increase in the temperature.

The residence time is one of the important factors that affects the reforming of ethanol and the production of hydrogen. The efficiency of the reforming increases with the increase in the residence time because the time of the reactions between the active ingredients and the molecules extends. When flow rate of the raw materials is very high, particles generated by the materials will leave a high electric field region in the short residence time, resulting in the particles leaving the discharge region before ionizing has been completed, thus the efficiency of the reforming reduces. However, if the residence time is too long, the reverse reaction will occur, which will also reduce the efficiency of the reforming.

Other factors, such as electric field, pressure, humidity, ozone concentration, the density of the electrons and the active ingredients, can also affect the effect of the fuel reforming. For example, since the electron collision caused the initial degradation process and generated the active ingredients, the density of the electrons is very important in the plasma reforming of alcohol [31]. Currently in order to obtain a more efficient reforming system, more and more factors are attracting the attention of researchers. Research conducted around other factors is very important and a lot of progress has been made.

2.4 Comparison of the Non-thermal Plasma Reforming of Ethanol

Table 2.1 lists the effects of all types of non-thermal plasma reforming of ethanol to produce hydrogen in the literature regarding the reforming conditions (discharge power, carrier gas, the amount of ethanol and the ratio of alcohol and water) and the reforming indicators (conversion rate of ethanol, selectivity of hydrogen, production rate of hydrogen and specific energy requirement (*SER*), etc.) and Fig. 2.1 also takes the production rate of the hydrogen and the energy consumption of per unit hydrogen production as indexes and intuitively reflects the differences on the hydrogen production performances of the ethanol reforming of different types of non-thermal plasma [1, 11, 13, 39–53]. To obtain a higher production rate of hydrogen during the reforming, the discharge device is required to have a larger amount of ethanol processing. The figure shows that the discharge types that have the largest amount of ethanol processing are glow discharge and non-thermal arc discharge, so these two types of discharge can obtain the maximum production rate of hydrogen. The discharge types that have the lowest energy consumption of per

Table 2.1 The effects of non-thermal plasma reforming of ethanol to produce hydrogen

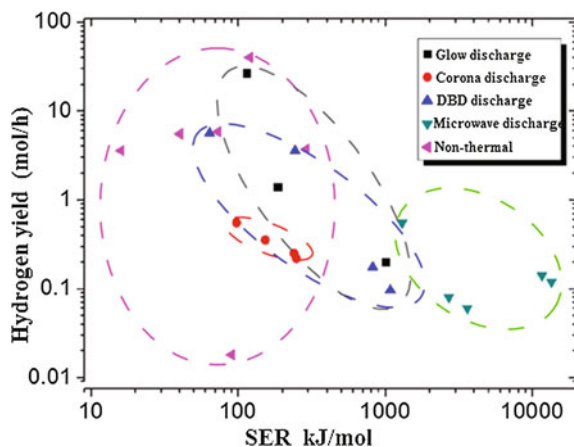
Discharge type	Discharge power (W)	Carrier gas	Ethanol flux (g/s)	Ethanol-H ₂ O molar ratio	Conversion rate (%)	H ₂ selectivity (%)	H ₂ yield (%)	SER for H ₂ (kJ/mol)	H ₂ production rate (mol/h)	References
Glow discharge	850	Ar	0.51	1/0.013	87	22	20	115	26.6	[39]
Liquid phase glow discharge	72	–	0.027	1/0.39	22	100	22	186	1.39	[46]
	56	–	1.31×10^{-3}	1/19	39	166	65	1008	0.2	[46]
Corona discharge	17	–	0.001	1/3.2	100	104	104	240	0.25	[40]
Corona discharge	~15	Air	1.32×10^{-3}	1/0	90.1	74–85	~70	249	0.22	[53]
Pulsed Corona discharge	~15	–	1.32×10^{-3}	1/6	99	115	114	153	0.353	[47, 48]
Pulsed Corona discharge coupled with catalysis	~15	–	1.32×10^{-3}	1/6	97	184	178	98	0.552	[48]
DBD discharge	100	Ar	0.053	1/0.85	–	–	45	64	5.6	[42]
DBD discharge	42	Air	–	1/0	30	105	32	–	–	[59]
DBD discharge	240	–	0.0247	1/1.08	65	94	61	244	3.54	[49]
DBD discharge	~30	–	2×10^{-3}	1/1.28	65–100	56	36–56	1080	0.096	[41]
DBD discharge	40	Air	2.4×10^{-3}	1/20	85–88	30–32	27	820	0.175	[50]
Surface	60	–	2.56×10^{-4}	1/0	~100	~100	~100	3600	~0.06	[51]
Microwave discharge	60	–	2.56×10^{-4}	1/3	~100	~133	~133	2700	~0.08	
Surface Microwave	200	Ar	6.1×10^{-5}	1/0	100	70–83	70–83	1300	0.55	[44]
Rotating Microwave discharge	450	Ar	5×10^{-4}	1/0	~99	96	95	13,500	0.12	[43]

(continued)

Table 2.1 (continued)

Discharge type	Discharge power (W)	Carrier gas	Ethanol flux (g/s)	Ethanol-H ₂ O molar ratio	Conversion rate (%)	H ₂ selectivity (%)	H ₂ yield (%)	SER for H ₂ (kJ/mol)	H ₂ production rate (mol/h)	References
Rotating Microwave discharge	450	Ar/Steam	5×10^{-4}	1/1.47	98.40	117	111	11,600	0.14	[52]
Non-thermal fixed arc discharge	100	Air	–	1/0	50	30	15	~100	–	[12, 19]
Liquid non-thermal arc plasma	300	Air	0.0256	1/2.56	100	62	62	291	3.7	[45]
Non-thermal fixed arc discharge	150–190	Air	0.03–0.14	1/0.82	49	104–129	51–64	~40	1.4–5.5	[1]
Pulsed dimensional Knife-shaped glidarc	0.45	Ar	$3-15 \times 10^{-6}$	1/3.83	–	–	8–28	90	0.012–0.018	[19]
Semi free rotating arc discharge	1200	Air	0.25	1/0	65	~55	35	106–120	~40	[11]
Scaling tube free rotating arc discharge	100–300	Air	0.1–0.35	1/1.6–8.0	50–90	~40	~30	73	5.8	[13]
Micro semi-non-thermal fixed arc	11–13	Air	0.1	1/0.88	56	24	13	16	3.56	[60]
Micro semi-non-thermal fixed arc	12–14	Air	0.1	1/2	81	40	32	6.7	7.96	[60]

Fig. 2.1 Comparison of reforming behaviors of hydrogen generation out of ethanol with various types of non-thermal plasmas [1, 11, 13, 40–54]



unit hydrogen production are non-thermal arc discharge and DBD discharge, wherein the energy consumption of per unit hydrogen production of non-thermal arc discharge is concentrated in the 40–100 kJ/molH₂. Comprehensive analysis shows that the non-thermal arc is a very good hydrogen producer in ethanol reforming. Taking all of the analysts into consideration, the non-thermal arc is a very good ethanol reforming hydrogen production process.

2.5 Developmental Trends of the Non-thermal Arc Plasma Reforming of Ethanol

As described above, the non-thermal plasmas all have a large number of high-energy electrons, so they can react rapidly with the particles that need to be treated in the reaction zone. However, this also leads to a lower selectivity of plasma reactions. In recent years, many studies have been dedicated to using the catalyst-assisted plasma system to overcome the aforementioned shortcomings and improve the reforming or processing efficiency of the plasma system. Currently catalytic-assisted plasma systems have been widely used in the field of methane reforming [55–57]. In addition, the Cu/ZnO/AL₂O₃ catalyst was added into the DBD discharge region and synergies between the two in the steam reforming of methanol were explored [58]. It was found that discharge can reduce the temperature that the catalyst needs to play its activity. The synergy between them is believed to originate from the catalyst's absorption of the intermediates of the plasma reaction. The spark discharge plasma-catalytic system was used to degrade dimethyl ether to produce hydrogen and it was found that hydrogen production can be increased significantly at a high temperature (50–700 °C) after adding the iron catalysts [59]. In addition, it was also found that the use of a catalyst can increase the discharge capacity. It is worth mentioning that the catalyst Pt/TiO₂ of the water

gas shift and the filler layer Pt–Re/TiO₂ were placed just below the cathode electrode, so that the catalyst can fully utilize the heat generated during the plasma reforming [48]. By selecting the appropriate operating conditions, the content of CO that was produced from the degradation of ethanol (about 30%) was decreased to about 0.8% at the airspeed of 12,000 cm³/(g•h), and the content of hydrogen in the gas production was up to about 73%, which means that after the removal of CO, the gas production can be used as hydrogen fuel cells. So in the future, combining the catalyst and the non-thermal arc to improve the load capacity and hydrogen production of the system can be considered, and the research should be focused on the exploration of the catalyst with low cost, long life and good performance. In addition, the reforming reactor needs to be further optimized in configuration and size, and to ensure the higher stability of the discharge and level of capacity, the density of the energy should be improved while reducing the size of the reactor; and the miniaturized reforming reactor or even the mini-reactor will bring more application fields, which will also bring more requirements and challenges for the plasma reforming reactor. Therefore, a combination of the catalyst, miniaturization, cost reduction and diversification and multifunctionality will be the trend of the future development of non-thermal plasma arc reforming.

Furthermore, because non-thermal plasma is very promising in fuel reforming, in the preparation of nanomaterial, in surface modification of material, in medical sterilization and in the treatment of environmental protection, it can be predicted that normalized and universal non-thermal plasma technology can be realized, paving the way for a low-cost, diversified and multifunctional non-thermal plasma process.

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