Received 9 November 2022; accepted 11 November 2022. Date of publication 23 November 2022;
date of current version 14 December 2022. The review of this article was arranged by Associate Editor M. Shiratani.

Digital Object Identifier 10.1109/OJNANO.2022.3223897

Review of Plasma Technologies for Contribution of Environmental Purification

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ABSTRACT Since the beginning of the 20th century, plasma technology has been used in a variety of fields. In the 1980s, R&D related to arc plasma welding and waste disposal, as well as etching, painting, and gas removal equipment that used plasma technology in the processes associated with semiconductor manufacturing. In the 1990s, research on removing air pollutants using atmospheric pressure plasma technology became active. In the 2000s, research on the application of thermal/non-thermal plasma technology to air pollution, waste and water treatment became active. Electrostatic precipitators (ESP) can remove a wide variety of particles such as soot from thermal power plants, coal, and oil mist, resin powder, glass powder, dust, and iron powder generated from incinerators, boilers, and various manufacturing plants. Waste treatment aims to reduce the volume of garbage, recycle incinerated materials, and utilize waste heat from incineration, and plasma technology is used in each process. Various techniques have been used for making purified water. Water quality requirements vary according to the objective. Plasma technology uses an electrical field to encourage seed germination and growth. Due to the spread of such applied technology, plasma technology has attracted attention again in recent years.

INDEX TERMS Non-thermal plasma, thermal plasma, pollution control, waste treatment, water treatment, harmful gases, plasma reactor.

I. INTRODUCTION

THE plasma technologies have been conducted in a wide range of fields, such as fluorescent lamps and air purifiers at home, also for industrial use such as semiconductors, electronic equipment, automobiles, metals, energy, construction, and waste disposal. Recently, it has expanded to the agricultural and medical fields by taking advantage of its characteristics.

As shown in Table 1, the plasma defined equilibrium/non-equilibrium plasma depending on the electron temperature and particle state [1]. Non-equilibrium plasma, is also defined low-temperature plasma or atmospheric pressure plasma, and it easily to generate and can be directly touched by hand [2]. Compared to thermal plasma, non-thermal plasma gas temperature is lower and the radicals generated in the plasma are denser, so that high reactivity can be expected and it's easy to apply industrial applications.

II. HISTORY OF PLASMA TECHNOLOGY USED IN INDUSTRIAL AREA

The oldest known industrial application of plasma technology is fluorescent lighting. In 1808, the arc lamp invented by Humphry Davy of England was used for street lighting [3]. And in 1840 the British scientist W. R. Grove invented the platinum filament incandescent light bulb and put it to practical use. Since then, the most famous for industrial use is the ozone generator (Ozonizer) invented by Siemens of Germany in 1857. Due to its excellent deodorizing, sterilizing, and decolorizing effects, ozone is used in various treatment fields such as clean water, sewage, industrial water, wastewater, air deodorization, pool water, food, seawater, and pulp wastewater. Plasma is deeply relating and commercialized those products and it's widely used around the world [4], [5].

Since the beginning of the 20th century, plasma technology has been used in various fields, and especially since the 1970s,

TABLE 1. Plasma Types and States, Examples of Applied Technologies

Type	Condition		P. (Torr)	T(eV)	Application
	Pressure	Temp.			
Thermal	High	High	>10	Te>Ti=Tg (>0.2)	Solid waste treatment, coating, water treatment, cutting/joining, fuel reforming, ultrafine particle production
Non-thermal	High	Low	>100	Te>Ti>Tg(<0.2)	Exhaust gas treatment, water treatment, waste treatment, polymer coating, fuel modification, surface treatment, ultrafine particle production
Material Processing	low	Low	<10	Te>Ti>Tg(<0.1)	semiconductors, lighting, lasers,

Te: electron temperature, Ti: ion temperature, Tg: gas temperature

TABLE 2. Cleanup Methods for Air Pollutants and Their Characteristics

	plasma density	Electron Temp.	Gas Temp.	electric Field	Treatment Flue Gases	Power Supply & Reactor	Improvements
Electron beam	Very High	Extremely High	Low	Very Low	Acid Gases, VOCs	DC → Pulse	Energy Efficiency
Barrier Discharge (silent/surface)	High	Medium	Low	Medium	Oxidation of VOCs or Acid Gases	Parallel plate Trench, Pyramid	Pressure Drop
Barrier Discharge (ferro-electric)	Low	High	Low	Very High	PFCs, Oxidation of VOCs	Shape of Pellets Sphere → Hollow	Pressure drop & Energy efficiency
Pulsed Corona	High	Medium	Low	High	VOCs	Pulsed corona Pulse Power	Electrons Energy
Pulsed power	Very High	High	Medium	High	Acid Gases		
Capillary	High	Low	Medium	Low	VOCs	DC → AC/DC	Stability
Flow stabilized Corona	Locally High	Locally High	Low	High	Acid Gases, VOCs, Toxic Gases		
Arc/Plasma Torches	Extremely High	Locally High	Extremely High	Low	ODS/VOCs* Toxic Gases	Lower power	Energy Efficiency
RF Discharge	High	Medium	High	Low	ODS/VOCs*	Inductive → Capacitive	Energy efficiency
Microwave Discharge	High	Medium	Medium	Medium	ODS/VOCs*	Cavity → Torch	temperature

plasma has become an indispensable technology in many manufacturing industries. In the 1980s, thermal plasma such as arc plasma that for welding and waste treatment became popular and research and development (R&D) enhanced. In addition, partly because the semiconductor industry was at its peak in Japan, a large number of products such as etching, painting, and gas removal equipment were produced using plasma technology in the manufacturing process.

In the 1990s, research on the removal of air pollutants using atmospheric pressure plasma technology became popular, and in Japan, with the support of RITE (Research Institute of Innovative Technology for the Earth), an international team was formed in anticipation of international expansion. As a result, many world-class research results were published [6], [7].

In the 2000s, research on the application of atmospheric pressure plasma technology had been conducting for water treatment. By generating plasma in water, a sterilization effect can obtain without using chemicals, and impurities can be removed, so R&D aimed at industrialization was promoted.

In the 2010s, application research to the medical industry became observed around the world. Plasma technology is also undergoing clinical trials for practical use in new fields such as cancer treatment. In addition, it has also put to practical use in the beauty field. Due to the spread of such applied technology, plasma technology has attracted attention again in recent years.

III. ENVIRONMENTAL PURIFICATION

The Table 2 shows the types of environmental pollutant treatment technologies using plasma and their characteristics. The following shows the trend for products in which plasma technology has been commercialized.

A. AIR PURIFIER FOR HOME USE

General household air purifiers widely used for air pollution and indoor air cleaning [8]. In particular, due to the global spread of COVID-19, sales of air purifiers have grown so much that production could not keep up with them for a while. When home air purifiers first went on sale, they primarily intended to remove suspended substances such as soot and pollen. But in recent years, the functions of air purifiers are expanding, PM 2.5 and virus removal, humidification and deodorization functions added. The products sold not only for

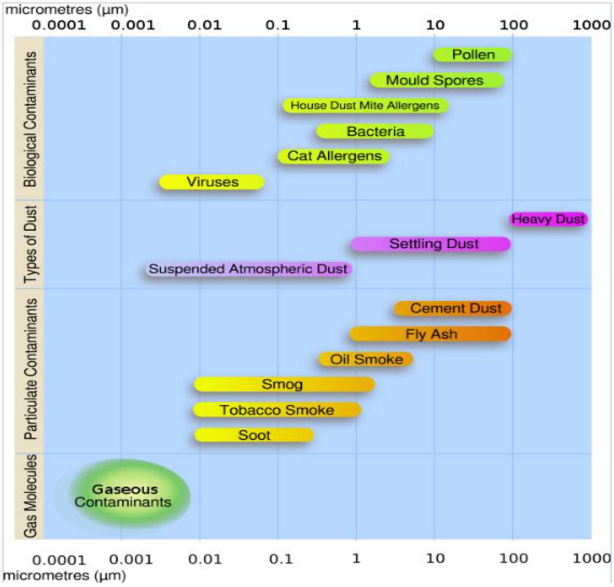


FIGURE 1. Size distribution of particles.

health considerations but also for the purpose of providing a comfortable living environment [9].

Fig. 1 shows size of particle that effect to health problem so that those particles need to remove it from atmosphere [10].

The air purifiers have been commercialized and each manufacturer mainly removes dust using a filter, and use plasma to improve dust removal efficiency, killing bacteria, VOC decomposition and a deodorizing function [11], [12]. Since maintenance such as filter replacement is also a point for consumers, there are differences in the handling and replacement frequency of filters for each manufacturer.

In recent years, plasma technology has installed in air conditioners, refrigerators, vacuum cleaners, washing machines, etc., and not only installation types but also easily portable types are being sold. IoT is also installed in air purifiers, and those with wi-fi control functions are also on sale [13].

Sharp's "Plasmacluster" contributed to popularizing the word "plasma". This technology generates active oxygen by plasma discharge, creates positive and negative ions, and removes pollutants in the air as shown in Fig. 2. It cuts and removes the smell of cigarettes, proteins such as the feces and carcasses of floating mites, reduces the action of allergens, removes viruses in the air, and cuts and decomposes the proteins of floating mold cell membranes [14], [15].

Panasonic Co. has a feature called "nanoe", and the generation mechanism is to cool the tip of a metal rod to condense moisture and apply a high voltage to it where generate an ultra-fine mist (OH radical), which kills bacteria. It suppresses viruses, pollen, mold, etc., and is also applied to beauty products because it has a moisturizing effect on the skin and hair [16].

DAIKIN Industries, Ltd. sells air purifiers that use an electrostatic precipitator to positively charge allergens such as mold, dust mites, and pollen, and filter [17].

B. ELECTROSTATIC PRECIPITATOR (ESP)

Electrostatic precipitators (ESP) can remove a wide variety of particles such as soot from thermal power plants, coal, and oil mist, resin powder, glass powder, dust, and iron powder generated from incinerators, boilers, and various manufacturing plants. ESP was commercialized by Cottrell in the United States in 1907 for collecting sulfuric acid mist. In Japan, heavy industrialization started in the 1910s, pollution problems caused by smoke emissions from factories began to emerge with the increase in electricity demand, and ESP was installed to those facilities. According to the Journal of the Institute of Electrical Engineers of Japan in 1921, nine ESP units are being used for industrial purposes in Japan. The domestic manufactured ESP became main products after Cottrell's patent expired in 1933 [18], [19].

ESP is roughly divided into wet type and dry type, and is installed in thermal power plants, chemical plants, etc. for the purpose of capturing fine particles in a wide space [20], [21], [22], [23]. Rather than using an ESP alone, it is often installed as part of an exhaust gas treatment system, and overall, it not only collects soot, but also removes NOx and SOx. In addition, ESPs installed at road tunnels also has been practical use [24], [25], [26], [27], [28], [29].

C. WASTE TREATMENT

Waste treatment aims to reduce the volume of garbage, recycle incinerated materials, and utilize waste heat from incineration, and plasma technology is used in each process [30], [31].

Thermal plasma technology is applied to fix incineration ash. A municipal waste ash melting system using this technology was installed at Matsuyama City in 1994 [32]. Since the characteristics of thermal plasma has high energy density and high temperature, the processing and reaction speed are high, and the amount of gas used is small, so that the generated by-products during processing exhaust gas treatment is small as well. In particular, it is characterized by being able to decompose and render harmless dioxins and organic halogens (chlorobenzene and chlorophenols), which have been a hot topic for a while [33].

Fig. 3 shows example of waste treatment system using plasma torch [34]. Arc plasma is also used for melting radioactive waste. A plasma melting and volume reduction treatment facility was installed at the Tsuruga Power Station for the purpose of processing low-level radioactive waste, and has been in operation since 2005 [35]. Thermal plasma technology is also used to decompose Freon, Halon, and PCB [36], [37].

D. WATER TREATMENT

Various techniques have been used for making purified water. Water quality requirements vary according to the objective. For example, drinkable tap water quality is subject to strict regulations. On the other hand, Industrial water, flush toilet water, and park fountains are not necessary as tight regulated quality as drinking water. Sewage such as domestic

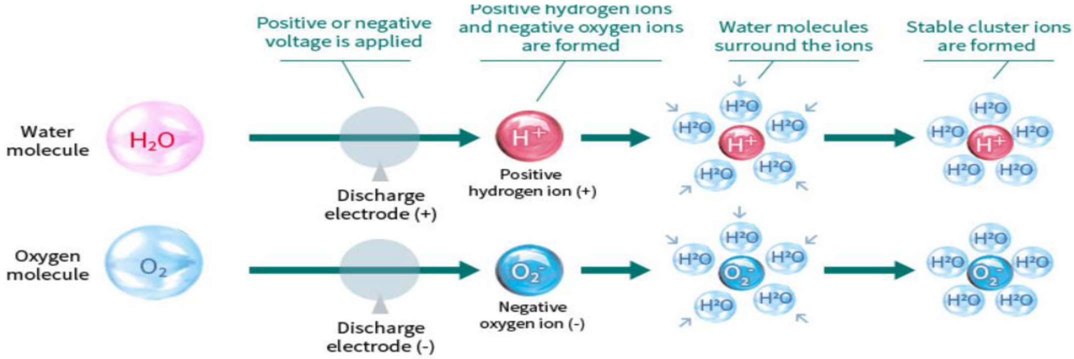


FIGURE 2. The mechanism of generating plasma cluster.

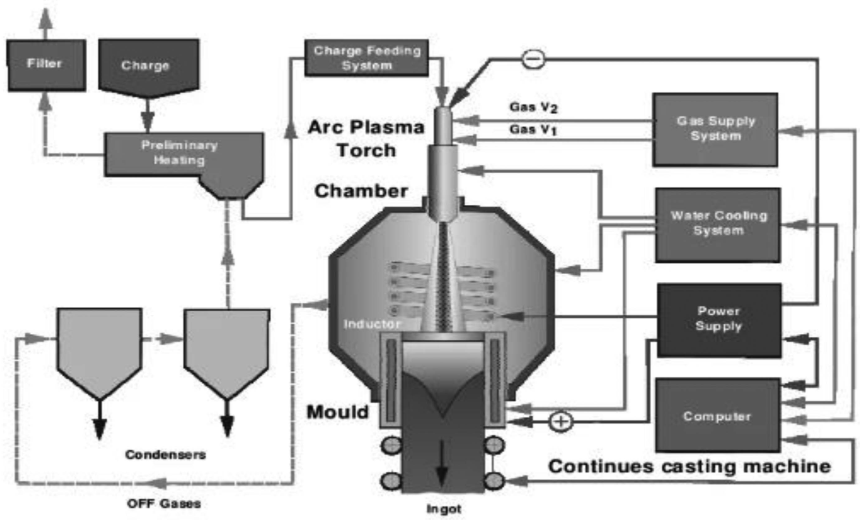


FIGURE 3. Example of plasma torch system for waste treatment.

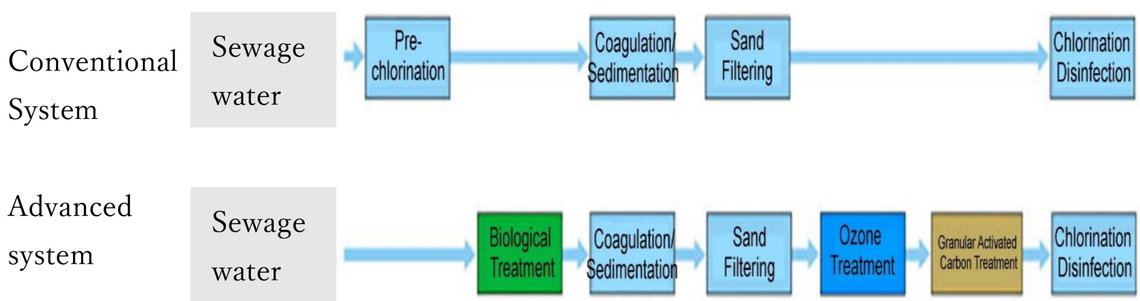
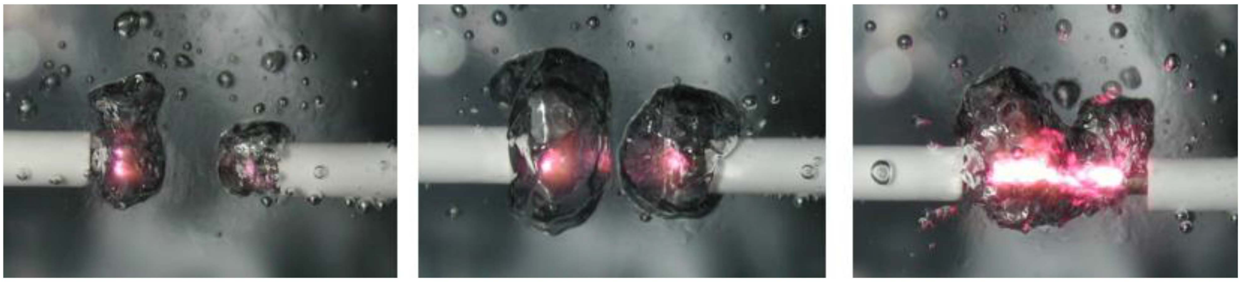


FIGURE 4. Comparison of conventional and advanced technologies for sewage water treatment.

wastewater, industrial wastewater, and rainwater treated through processes according to each quality, and finally discharged into rivers. Plasma technology has been contributing such processes and especially for less or no chemical usage as shown in Fig. 1 [38].

The tap water is supplied by treating raw water with ozone and activated carbon [39]. The sewage is settling basin, then removing large garbage and sand, and then mixing microorganisms (activated sludge) with the sewage and purifying it while aerating as shown in Fig. 4. After that, the water may be treated to further remove organic substances, nitrogen, and phosphorus that cause water pollution. Finally, after disinfecting the supernatant water of the final sedimentation tank, it is discharged into rivers and the sea as treated sewage water. Through this process, sewage returns to the natural water cycle [40].



(a)Dielectric breakdown in bubbles (b) expansion of air bubbles (c) Bubbles coalesce to form streamer discharge

FIGURE 5. **Generation of solution plasma.**

The Ozonizer used for such water and sewage treatment was invented by Siemens of Germany in 1857. Since then, in order to improve efficiency, various companies have changed the shape of the electrodes and devised reactors, which have been put to practical use [41], [42], [43], [44]. Ozone has a strong oxidizing power and has sterilizing and deodorizing effects, so it is used in a wide range of industrial fields such as water purification plants and food sterilization [45], [46]. Recently, household ozone generators with various effects such as "sterilization and deodorization of indoor space" and "removal of food additives and pesticides by generated ozonated water" have been commercialized. The upper limit of U.S. FDA and Japan Air Cleaning Association is 0.05 ppm, and the value shall be less than 0.1ppm recommended by the Japan Society for occupational Health [47].

In recent years, R&D is progressing toward the practical use of technology that generates plasma in water to treat water as shown in Fig. 5 [48]. For example, when removing foreign substances such as shellfish existing in water pipes, there is concern that other organisms may be affected if chemicals are used. Therefore, the generated plasma underwater is attracting attention as a technology that does not allow foreign matter to stay in water [49], [50], [51].

When plasma is generated in water with a constant frequency using a pulsed power supply, phenomena such as bubble and UV generation are observed. This generated UV has a sterilizing effect and also generates a shock wave, which prevents shellfish from settling in. It is attracting attention as an environmentally friendly technology because it does not use chemicals. At the same time, it is also possible to effectively inactivate blue-green algae. Observation of cells after plasma treatment revealed that the cell wall and membrane structure remained, and the intracellular alveoli disappeared [52], [53].

In this way, R&D are underway to put into commercialization a device that uses pulse discharge technology that can simultaneously generate shock waves and UV [54].

E. APPLICATION TO AGRICULTURE

In Japan, we often hear that places with a lot of Lightning (thunder) produce superior quality rice and grow well.

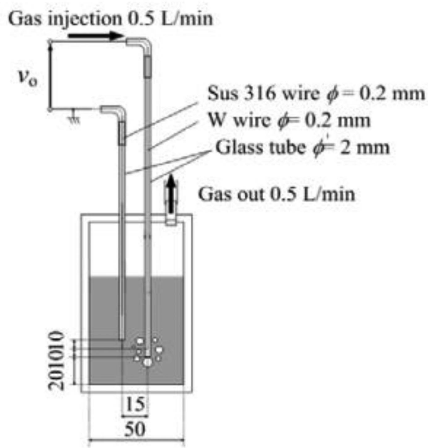


FIGURE 6. **A schematic of the reactor.**

Lightning is also a type of plasma, and research into applying this phenomenon to agriculture is gaining momentum.

Plasma technology uses an electrical field to encourage seed germination and growth. The electrostatic spraying, weeding, electrostatic pollination, increased fungal production, sterilization of hydroponics, seed sterilization, fruit surface sterilization, electrostatic sorting has been studying as application of plasma and generated ion wind by plasma is one of the key issues for those technologies. Also, It can be used for promoting drying, maintaining the freshness of fruits and vegetables, and removing dust from agricultural facilities [55], [56], [57].

At Iwate University, research conducted on how plasma irradiation improves the yield of mushrooms and preserves the freshness of fruits, vegetables, and seafood. Their technology in practical use is commercialized [58], [59]. For example, the experimental apparatus and results as shown in Figs. 6 and 7 [60]. In this experiment, the reactor generate the plasma within the drainage water. The drainage water from the bedpot emptied into the plasma reactor and then was treated by plasma irradiation, with the plasma produced in the glass tube and in the air bubble injected into the water through the glass tube. In Fig. 6, a device for preparing plasma-treated water to be given to plants, and plant leaf size has increased with

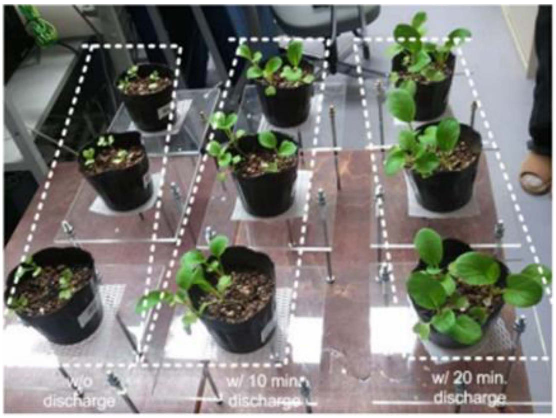


FIGURE 7. Photographs of Brassica rapa var. perviridis cultivated for 28 days at (a) w/o plasma and with (b) 10 min. or (c) 20 min. of irradiation per day.

changing plasma irradiation time in the water as shown in Fig. 7.

In addition, various research institutes have reported the sterilization effect of agricultural products and water by plasma irradiation [61], [62].

IV. CONCLUSION

In the 1990s, research on removing air pollutants using atmospheric pressure plasma technology became active, and in the 2000s, research on the application of atmospheric pressure plasma technology to water treatment became active. In the 2010s, application research to the medical industry became popular in countries around the world.

Plasma technology is also undergoing clinical trials for practical use in new fields such as cancer treatment. In addition, it has also been put to practical use in the beauty field. Due to the spread of such applied technology, plasma technology has attracted attention again in recent years [63], [64], [65], [66], [67]. As described above, plasma technology has been put to practical use in various industrial fields, and R&D are being conducted for commercializing use in new fields.

Plasma technology is not new but include many applications and new fields so that it attracts key technology for developing better future.

ACKNOWLEDGMENT

Author thanks to emeritus Prof. Osamu TAKAI who gave me Fig. 5 photo and many advice. Also, Prof. Koichi Takaki who provide me Figs. 6 and 7 with discussion.

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