Industrial Applications of Pulsed Power

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Recent developments of pulsed power generators have been concentrated into the developments of repetitively operated pulsed power generators. In addition, the stability and quality of the pulsed power output have been pursued. The developments of these high-quality pulsed power generators enable the industrial applications of pulsed power. Industrial applications are described in the fields of environmental, medical, nanotechnologies and recycling applications.

Keywords: pulsed power, industrial applications, environment, recycling, nanotechnology, plasma, discharge

1. Introduction

Single-operated pulsed power generators with an extremely high peak power have been developed for military and nuclear fusion applications since the First International Pulsed Power Conference in 1976. These efforts produce a new approach of the inertial confinement nuclear fusion researches using X-ray radiations from Z-pinched plasmas produced by the pulsed power.(3)

Recently, repetitive-operated pulsed power generators with a moderate peak power have been developed for industrial applications. Not only the stability and quality of pulsed power outputs but also the lifetimes of pulsed power generators are important for industrial applications. The development of pulsed power generators optimized for industrial applications causes researches of many kinds of applications of pulsed power.

In this paper, the recent researches for industrial applications of pulsed power are described, especially, in the fields of environmental, medical, nanotechnologies and recycling applications.

2. Environmental Applications

2.1 NOx Treatment Non-thermal plasmas at atmospheric pressure have been widely used for the treatment of pollution gases such as NOx, SOx, VOCs and dioxin, and for the generation of ozone in last decades. The pulsed streamer discharge is one of non-thermal plasmas and is well known as it can generate the chemically active species (= radicals) which react with pollutants, such as N, O and OH, efficiently.(54-47) In the case of the pollution control by pulsed streamer discharges, the pulsewidth of the applied voltage to the discharge reactor has the strong influence on the energy efficiency for reduction of pollutants. Figure 1 shows the dependence of NO removal efficiency on the NO removal ratio for different pulsewidths.(5) In this experiment, the peak applied voltage is fixed at a constant value for all pulsewidths, and the coaxial discharge reactor having the same geometry is used. The NO removal energy efficiency decreases with the NO removal ratio because the energy requirement (= pulse repetition rate) increases. At a fixed NO removal ratio, the NO removal efficiency is higher for the shorter pulsewidth. In the progress of the pulsed streamer discharges in a coaxial reactor, firstly the streamers initiate at the surface of the inner wire electrode and then propagate keeping a high electric field toward the outer cylinder electrode. After fully development of the streamers between electrodes, a large current flows though the plasma channels by the streamer propagation.(6) Consequently, the radicals are generated efficiently during the propagation of streamers. The reason, why the shorter pulsewidth has the better performance for NO removal, is due to the reduction of the large current flow after the streamer bridges the electrode gap.

2.2 Cryptosporidium Treatment Cryptosporidium contaminates water around the world. It is difficult to remove it with the conventional water treatment processes, and cryptosporidium is extremely resistant to the methods of chemical disinfections typically used to inactivate these microorganisms. The cryptosporidium has been treated by pulsed power.(78) Figure 2 shows a schematic diagram of the experimental set-up. A new
technology for inactivating cryptosporidium oocysts has been developed by using pulsed arc discharges in water, which generate shock waves, UV emissions and radicals. The pulsed arc discharges are generated between two stainless steel rod electrodes, 6 mm in diameter and 2 mm in gap separation. This method has been applied to the inactivation of oocysts in the backwash water from a sand-filter unit of drinking water plants. The results indicate that the major factor influencing inactivation is UV emissions, and that more than 99% of the oocysts in the high turbidity backwash water are inactivated with an energy density of 0.24 kWh/m³.

2.3 Algae Treatment

The streamer discharges in atmospheric pressure gases have been used for the treatment of exhaust gases, the removal of volatile and toxic compound such as dioxin, and at the sterilization of microorganism. The algae called “Aoko” in Japanese appear in summer and cause environmental problems. A large volume streamer-kind discharge in water is used for the algae treatment(9). These streamer-kind discharges in liquids are able to produce a high electric field, high energy electrons, ozone, chemically active species, ultraviolet rays and shock waves, which readily sterilize microorganisms and decompose molecules and materials. An all solid state pulsed power system for the algae treatment is shown in Fig. 3. The developed mobile system consists of a photo-voltaic generator, a Pb battery, an inverter, a controller, a command charger, a high-speed thyristor, a magnetic pulse compression circuit, a Blumlein line type pulse forming network (B-PFN) and a pulse transformer, and generates an output peak voltage of over 100 kV with a voltage rise time of 200 ns. The algae have been successfully treated by the large volume streamer-kind discharges, which are produced by the developed mobile system with simple point-to-plane electrodes.

3. Medical Applications

3.1 NO Generation

After NO was identified as the endothelium-derived relaxing factor (EDRF) in the human body in 1987(10), it has been widely used to the medical treatments of the acute respiratory distress syndrome (ARDS), the acute lung injury, the persistent pulmonary hypertension of the newborn and other related illnesses(11). Currently, the inhalation system of NO includes a nitrogen cylinder with a high concentration of NO. For the safe NO inhalation system, an on-site NO generator is necessary to avoid the accidental leak of NO from the cylinder. In this section, a NO generation system using pulsed arc discharges is introduced briefly.

Figure 4 shows the dependences of the NO and NO₂ concentrations, and the ratio of NO/NOx (=NO+NO₂) at the outlet of discharge reactor on the percentage of O₂ in mixture of N₂ and O₂. N₂ and O₂ are used as feeding gases to the discharge reactor(12).

It is found from Fig. 4 that the maximum concentration of NO and the highest NO/NOx are obtained at 35% and 20% of O₂ in the mixture, respectively. In the medical applications, NO₂ has to be removed completely from the gases feeding to patients because it is harmful for human. Therefore, it is desirable that the ratio of NO/NOx is a higher value. Note that the dry air including 20% of O₂ is the best gas for the NO generation by pulsed arc discharges. Figure 5 shows the NO production system developed at Kumamoto University(13). This system consists of a cylinder of dry air, a mass flow controller, a discharge chamber, a pulsed power...
generator, a NO₂-NO converter, a charcoal filter and a particle filter. It produces enough concentration of NO in the dry air for the medical applications.

3.2 Tumor Therapy Cells are complex matter and consist of plenty of organelle, macromolecular and cytoplasm. From the view point of their electrical property, the cell can be expressed as Fig. 6. The cell membrane, which is thin and high resistance compared to the cytoplasm, works as a capacitor, and others are regarded as the resistive. Therefore, the electric response of the cell depends on the frequency of the applied electric fields (β dispersion). When the step function voltage is applied to the cell, charges are accumulated at the membrane and the voltage across the membrane is increased. For the negligible membrane conductance, the charging time, τₐ, of the spherical cell membrane is given as

\[ \tau_a = \frac{1}{2 + \rho_s} C_m a \]  

where \( \rho_s \) is the resistivity of the suspending medium, \( \rho_c \) the resistivity of the cytoplasm, \( C_m \) the capacitance of the membrane per unit area, and \( a \) the cell diameter. The fundamental frequency of pulsed electric fields (PEF) is determined by the pulse width. In case the pulse width is longer than \( \tau_a \), or the frequency is smaller than \( 1/\tau_a \), the electric field is induced across the membrane, which results in the pore formation of the membrane (electroporation). The electroporation is well known technique as a cell manipulation, for example, the gene transfection, cell fusion, drag delivery into the cell. On the other hand, the pulsed electric fields, the width of which is shorter than \( \tau_a \) or the frequency is larger than \( 1/\tau_a \), generate the intracellular electric current flow. The intracellular current or electric field might give influence on DNA directly for example. The pulse electric field or alternating field is capable of giving an effect to specific components of the cell with choosing an appropriate pulsed width or frequency.

Some research groups are trying to utilize the intracellular effect of the pulsed electric field for the cancer therapy. The intracellular effect is expected to stimulate the DNA and to initiate the programmed death (apoptosis) of the cancer cell.

Figure 7 shows the PEF treatment of tumor therapy using mouse conducted by Schoenbach and Beebe. The 300 ns wide voltage pulses of 30 kV are applied to a tumor grown in a mouse. Size of the tumor is reduced few weeks after the treatment(13). Pulse electric fields and high frequency fields have a huge potential to contribute in the biological/medical fields.

4. Nanotechnologies Applications

4.1 Excimer Laser for Lithography Hydrogen thyratrons have become to be well used as high power, high repetition rate and long life discharge switches in radar modulators and pulsed lasers. However, the thyratron lifetime is much shorter than that requested as industrial lasers. Recently, researches on practical industrial applications of high-repetition-rate pulsed power generators have been done by using semiconductor switches and a magnetic pulse compression circuit (MPC). One of applications is an excimer laser for lithography. The lithography technology using the excimer laser is the main player of a LSI patterning process from 250 nm to 70 nm node. The development of a pulsed power generator with a long lifetime, high stability and high repetition rate is important for the introduction of this laser into large mass production lines. A schematic circuit of an all-solid-state pulsed power generator to excite excimer lasers is shown in Fig. 8.

It’s generator uses a charger that can provide a rapid charge when the primary capacitor \( C_p \) requires. When a semiconductor switch (GTO) is turned on, a primary current pulse with a duration of about 4 μs is generated. Stepping up the voltage with the pulse transformer PT, the capacitor \( C_1 \) is charged with a negative high voltage pulse. Then the two-staged magnetic pulse compression circuit (MPC) performs pulse compressions. A peaking capacitor \( C_2 \) is charged rapidly, and then the high-speed and high-voltage pulse is applied to the laser discharge electrodes. The repetition rate of this pulsed power generator is 1 kpps. Nowadays the high repetition rate of excimer lasers for lithography attains to 6 kpps.

Fig. 6. Schematic illustration of cell and its electrical equivalent circuit ; \( C_s \) and \( R_s \) are capacitance and resistance of suspension, respectively ; \( C_m \) is the capacitance of cell membrane ; \( G_a \) and \( V_a \) express the function of ionic channels existing in the membrane. \( R_s \) is resistance of cytoplasm(14)

Fig. 7. PEF treatment of tumor grown in a mouse ; Needle electrodes are injected into a tumor, and 60 ns wide pulsed voltage with an amplitude of 30 kV is applied to the electrodes

Fig. 8. Excimer laser exciter using two stage MPC
4.2 EUV Light Source for Lithography

An extreme ultraviolet (EUV) with a wavelength of 13.5 nm is expected as a light source for the 45 nm or less rule photolithography process in the semiconductor manufacturing. The average EUV power of 115 W in bandwidth of 2% is required for the high volume manufacturing device. The EUV light is irradiated from the high energy density plasmas with the density of $10^{18} - 10^{19}$ cm$^{-3}$ and the temperature of 20 - 40 eV, which are produced by an intense pulsed laser or a pinch scheme of strong electrical gaseous discharges. Presently, the gas discharge produced plasmas (GDPP) based on Z-pinch scheme have achieved 50 W, that is much more powerful than achieved by the laser produced plasmas (LPP).

We have developed a compact Z-pinch device to improve the conversion efficiency (CE) from the electrical energy input to the EUV emission. In order to produce high energy density plasmas efficiently, the dynamic compression of the plasma is so important that the plasma must be driven by a low inductance pulsed power circuit. Figure 9 shows the cross sectional view of the Z-pinch device including a driving circuit, which has been developed at Kumamoto University. The discharge chamber is located at the center of the driving circuit, which is capable of delivering the sinusoidal current waveform with amplitude up to 34 kA and duration of 110 ns to the short circuit load. A 42 nF capacitor bank is charged up by the magnetic pulse compressor (MPC). A driving circuit operates with a high repetition rate of kHz range because a magnetic switch is installed.

Figure 10 shows the emission spectrum from the Z-pinched Xe plasmas. There are three major peaks at 11, 13.5 and 15 nm, which are associated with Xe$^{+1+}$, Xe$^{+10+}$ and Xe$^{+9+}$ ion species, respectively. Sn and Li are intensively investigated as an emitter because they have strong emissions at 13.5 nm. Figure 11 shows the EUV energy per shot as a function of Xe flow rate through the chamber. The EUV emission depends on so many factors, such as the current waveform, electrode geometry, and gas flow speed. Therefore, it is important to control the plasma parameter on the basis of the understanding of the plasma dynamics and radiation physics in order to improve the CE.

5. Recycling Applications

5.1 Concrete Recycling

In Japan, the recycling ratio of concrete scraps has been kept over 98% after the Law for the Recycling of Construction Materials was enforced in 2000. In present time, most of concrete scraps have been recycled as a lower subbase course material. However, the concrete scraps are predicted to increase rapidly and exceed the demand of road subbase in the near future. To promote the recycling of concrete scraps, the technology to produce the recycled coarse aggregate with high quality must be developed.

The heating and rubbing method is a developed method to produce the recycled aggregate. However, it is a problem that much energy is consumed to heat and rub the concrete. Here, a new method to create a high quality recycled aggregate by the shockwave generated from electrical discharges in water is presented.

Figure 12 shows the process of recycling coarse aggregates by the discharge and shockwave treatment. It is observed from Fig. 12 that the high quality recycled aggregate has been produced after a hundred shots treatment. In this case, the absorption ratio of the recycled aggregate is 0.95 (0.49: original aggregate) which is the sufficient value for TS A 0006:2004. In this method, a hand-made Marx generator (0.80 μF-40 kV, 10 stages) is used to generate the electrical breakdown between the point and the hemisphere electrodes in tap water. The gap distance between electrodes is 150 mm.
5.2 Recycling of Circuit Board  
Shock waves due to pulsed power discharges in water can be applied to destroy and separate electronic parts from circuit boards in reused electric appliances[23]. In case of a complex object which has interfaces between two materials which have different acoustic impedances, shock waves cause the mechanical stress at the interface between two materials and possibly separate them if the stress is larger than the attachment force. A material fragmentation technology using the pulsed power generated shock waves has the following advantages to the conventional methods, 1) repetitive operation, 2) electrodes are independent of the object, 3) comparatively harder object can be treated. Figure 13 shows the discharge vessel including a high voltage rod electrode and a semi-sphere mesh electrode immersed in water[24].

A reused circuit board is placed between electrodes. A positive polarity high voltage pulse exceeding 400 kV generated by a Marx generator is applied to the electrodes with the distance of several cm. Figure 14 shows the fraction of the circuit board after exposures to 500 discharges. The circuit boards have been successfully broken into small pieces, and the circuit elements have been separated from the boards. The amount of fragmentation is dependent on energy supplied from the Marx generator.

6. Summary

The development of repetitive-operated pulsed power generators with high-quality enables the many kinds of industrial applications of pulsed power. Recent researches of industrial applications are described, especially, in the fields of environmental, medical, nanotechnologies and recycling applications. Some of them are already commercialized. In order to commercialize many pulsed power applications, it is important to be applications that can not be realized without pulsed power.

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