A Novel Concept of Remediation of Polluted Streams Using High Energy Density Glow Discharge (HEDGe)

Alex Pokryvailo
(Spellman High Voltage Electronics Corporation 475 Wireless Boulevard E-mail: Apokryva@spellmanhv.com)

Abstract: Effluent gases containing various pollutants are generated from many sources. Non-thermal plasmas, including pulsed nanosecond corona (PC), were suggested for simultaneous removal of particulates and gaseous pollutants. PC demonstrated high removal efficiency, also in pilot-scale installations, but the cost of pulsed power supplies remains prohibitively high for most applications. With the purpose of reducing capital costs, DC flow-stabilized coronas had been proposed. Known devices employ linear flow and thus the residence time is very short. Spellman High Voltage Electronics Corp. has patented an approach to creating a flow-stabilized discharge in large volumes required by industrial applications. The main idea is providing a fast velocity gas flow in the vicinity of the ionizing electrodes that may be similar to those used in commercial ESPs, using rotational mechanism rather than longitudinal flow. Several designs are envisaged and discussed depending on the application, whereas either HV electrodes or grounded electrodes or both are rotated relative to each other in the same or opposite directions. Expected results and challenges are presented.

Keywords: Power source, corona, glow discharge, plasma cleaning

1 INTRODUCTION

Effluent gases containing sulfur dioxide (SO_2), and/or nitrogen oxides (NO_x), and/or particulate matter and/or volatile organic compounds (VOCs), sometimes in an aerosol phase, are generated from many sources including power plants, various combustion installations, e.g., diesel engines, steel plants, paper mills, landfills, painting and semiconductor plants, and the like. Many processes are known for the removal of these pollutants from the effluent gas before they are released to the atmosphere. For example, many coal-burning electric power utilities make use of wet or dry scrubbers for SO_2 removal, cyclones, bag filters, dry and wet electrostatic precipitators (ESP), catalytic converters for NO_x removal, etc. Pulsed nanosecond corona (PC) along with other kinds of Non-Thermal Plasma (NTP) was suggested for simultaneous removal of particulates and NO_x and SO_2 [1] as well as for destruction of VOC [2]-[4]. The approach of [2], [4] also makes possible the remediation of liquid streams by the atomization of the polluted liquids with the following processing by PC in the aerosol phase. PC demonstrated high removal efficiency, also in pilot-scale installations (see [5] and its bibliography), but the cost of Pulsed Power Supplies (PPS) generating nanosecond pulses remains prohibitively high for most industrial, especially large-scale applications. With the purpose of refraining of using such PPS, Hoag [6], Akishev [7]-[9] and Ren [10] proposed to use DC coronas in conjunction with a high velocity gas flow, typically in the range of 50 m/s-100 m/s. Such a flow stabilizes the corona discharge bringing it closer to an Atmospheric pressure Glow Discharge (AGD) mode and allowing for an order of magnitude higher specific power to be deposited in the treated media. Attempts also were made to increase this parameter by using resistive electrodes, ballasting multiple gaps, shaping anode region in a form of a spherical crater, etc. Compared to DC coronas, good cleaning results were demonstrated [7]. This was partially attributed to the current conduction mechanism that was effected mainly by free energetic electrons. The devices described in published literature employ linear flow and thus the gas residence time is very small. They also require high-power gas compressors; we believe for the above reasons AGD was not commercialized in cleaning applications.

It is important to note that NTPs have a very generic simultaneous action against a wide variety of pollutants. As a rule, if a device is efficient for removal of agent X it would be equally efficient, in relative terms, in the removal of agent Y. Published literature abounds in results proving this point. Our research on the subject can be found in [4], [11]. Therefore, we strongly believe that base-lining an NTP technology with any cleaning application, e.g., treating diesel exhaust, will give an unambiguous answer as to the cleaning efficiency (again, in relative terms) for the widest range of pollutants.

2 DESCRIPTION OF PROPOSED TECHNOLOGY

Spellman High Voltage Electronics Corporation has patented a practical, cost-effective approach to creating a flow-stabilized High Energy Density Glow discharge (acronym HEDGe) in large volumes required by industrial applications.

The Technical Goals of the technology are as follows.

- Flexibility and scalability; suitable for cleaning both gaseous and liquid streams.
- Dramatic reduction of the cleaning device size (a factor of two-three in volume is expected).
- Synergetic removal of particulate matter and destruction of hazardous chemical substances (SO_x, NO_x, VOC, etc.).
- Low capital cost compared to Pulsed Corona

technology.

- Large treatment capacity and synergetic action compared to other plasma technologies (barrier discharge, pellet bed, etc.).

It is anticipated that the scope of applications will be very wide; a partial list is given below:

- Electrostatic precipitators with synergetic DeNO_x and DeSO_x for flue gas processing;
- Cleaning of exhausts of large internal combustion engines;
- Conditioning of industrial incinerators exhaust;
- VOC destruction in gaseous and liquid effluent streams of chemical, electronic, textile, food and other industries;
- Odor abatement.

The main idea is providing a high velocity gas flow in the vicinity of the ionizing and/or low-curvature electrodes that may be similar to those used in commercial ESPs, using rotational mechanism rather than longitudinal fast flow. Several designs are envisaged depending on the application, whereas either HV electrodes or grounded electrodes or both are rotated relative to each other in the same or opposite directions.

Several chosen conceptual designs will be described. It will be clear from the discourse that many more implementations are feasible. Reference is first made to Fig. 1, which shows the device cross-section in two projections. Grounded cylinder 1 serves as a duct for the polluted stream, low-voltage wire electrodes 2 are attached to it by means of conducting spacers 3. High-voltage wire electrodes 4 are attached to a conducting shaft 5 by means of conducting spacers 6. High voltage power supply (HVPS) 7 is connected to the electrodes 2 and 4 either directly or via cylinder 1, shaft 5 and spacers 3 and 5. Polluted stream 8 is introduced into the interelectrode space. Motor 9 rotates both cylinder 1 with electrodes 2 and shaft 5 with electrodes 4 at the same angular speed ω in the same direction. In such a way, the electrodes 2, 4 cross the stream at high linear speed that is kept preferably in the range of 50-100m/s. The rotational speed is determined by the diameter. For instance, the linear speed of 50 m/s at 3000 rpm corresponds to a diameter of $1/\pi$ m, which can be realized with conventional electric motors. The centrifugal forces benefit the removal of particulates in this embodiment. The residence time is not different from that of conventional devices, contrary to the fast linear flow schemes of [7]-[10]. The distance D between wires 2 and 4 is chosen in such a way that an AGD would be formed upon the application of high voltage.

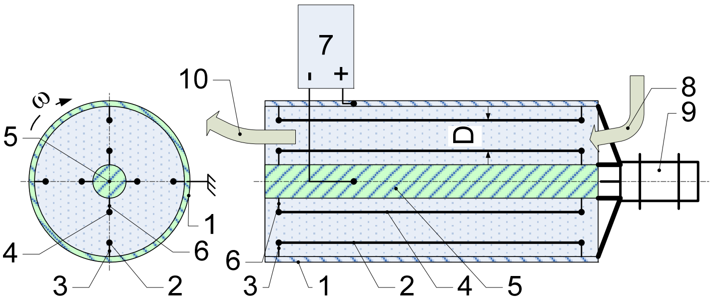

Fig. 1 Concept of HEDGe device. Both electrodes are ionizing

This distance depends on the amplitude and form of high voltage, be it DC, AC or pulsed voltage or superposition of the above, velocity of the electrodes, gas pressure and temperature, particulate content, etc. Distance D may be graded, being increased downstream, towards the stream outlet 10, in view of the decrease of the electrode speed relative to the gas caused by the gas entrainment, and formation of ionized species, whose concentration increases towards the stream outlet 10 [10]. Alternatively, two separate motors can be provided to rotate the assemblies of low voltage and high voltage electrodes in the opposite directions or at arbitrary speed in any direction. HVPS may be rotated together with the electrodes or connected to them, for instance, via slip rings. Both these options present technical challenges: fixed connection implies high mechanical stresses in view of acceleration, and slip rings at high voltage need adequate insulation.

We note here that plasma characteristics at such conditions as depicted in Fig. 1 and similar implementations below were not studied before. Since the electrode distance changes dynamically, the resulting effect may be similar to PC, however, with time constants of the order of hundreds μs. For instance, at a linear speed of 50 m/s and a characteristic travel of 0.05 m, the time constant is 0.05 m/50 m/s=1 ms. The load current will pulsate, and the HVPS will have to accommodate these variations. Operating the discharge in a high velocity stream complicates the picture even more.

Fig. 2 shows a device similar to Fig. 1, whereas the low voltage electrode is implemented as the outer cylinder. In this case, the electrode system approaches a wire-to-plane system, and the gap does not vary in time.

It is noted in [8] that the glow-to-spark transition may be largely governed by the instabilities of the anode plasma layer. If the cylinder is rotated relative to the incoming stream, breaking the anode instabilities becomes feasible.

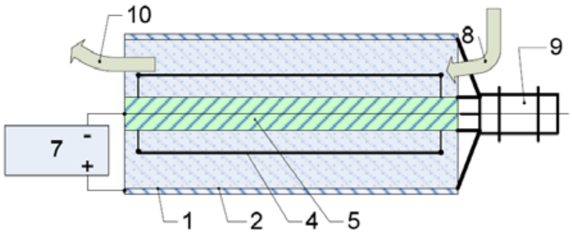

Fig. 2 Same as Fig. 1, anode electrode non-ionizing

Fig. 3 shows the device with a bipolar HVPS 7 that provides the voltage output of positive and negative polarity symmetrical relative to the grounded duct cylinder. The shafts can be rotated in the same or in the opposite directions. Insulating separators 14 can be furnished to effectively block the passage of flow via region 15, where the electrodes 4 and 12 do not overlap, and the discharge is feeble or absent due to weak electric field. In this way, the main part of the polluted stream passes the discharge zone.

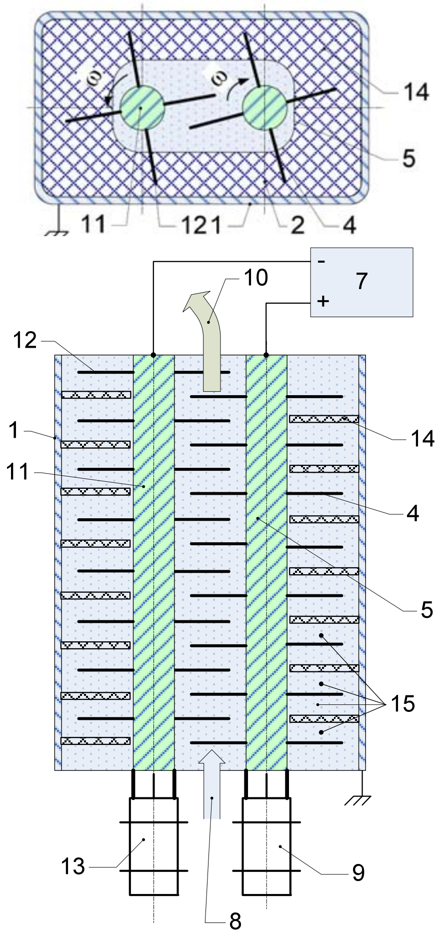

Fig. 3

This embodiment is particularly suitable for the remediation of streams containing no particulates. If the electrodes are long, the gas entrainment may occur, and then the traverse speed component will decrease downstream. An improvement in this sense can be made by segmenting the device in axial direction, which is exemplified by using the design Fig. 2 as shown in Fig. 4. Duct 1 and wires 2 are sectioned into two parts as designated by the reference numbers 1, 1A, 2, 2A, etc., respectively, and are rotated by their corresponding motors 9 and 9A in the opposite directions. As an additional benefit, in such a way, the total rotational moment of the device is brought to zero, and the tangential component of the stream velocity accumulated due to the flow entrapment is effectually used in the consequent section.

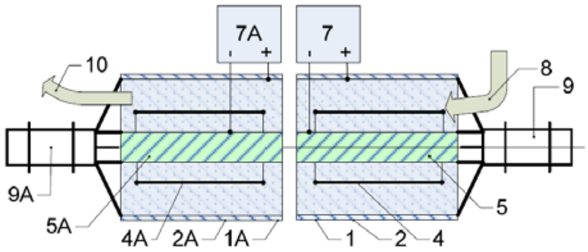

Fig. 4 Sectionalizing for reducing gas entrainment

All the above versions suffer from one serious shortcoming: the HV electrodes have to be rotated. As such, they have to be supported by powerful insulators, and the HV connections are problematic. Fig. 5 presents a version, where, with the objective of eliminating the movement of the HV electrodes, the grounded electrode 2 is divided into 3 sections, one of which 16 is rotated, e.g., by means of a belt 17 connected to the motor 9, and is supported on the stationary grounded sections 18, 19 by bearings 20, 21. High potential electrode 5 is suspended by insulators 22 attached to the stationary sections 18, 19. Insulators 22 have openings, e.g., being implemented as cones having spokes, to allow passage of flow 8. In this figure, the polluted stream is introduced from above as may be the case also for all implementations.

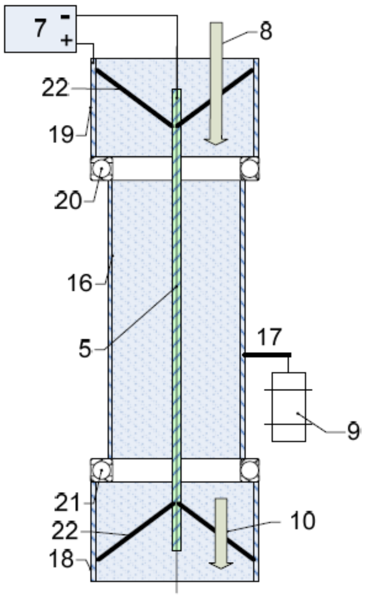

Fig. 5 Scheme with stationary HV electrodes

With the purpose of increasing the device treatment capacity, a checker mesh structure can be used as shown in Fig. 6 presenting the device cross-section. This design is similar to the electrode systems used in [2], [4], [11]. The discharge zone is between the HV pins 12 installed on stationary shafts 11 and ground potential pins 4 rotated by shafts 5. The latter may be rotated in the same or in the opposite directions. In the axial direction, the electrodes' structure is similar to that of implementation Fig. 3.

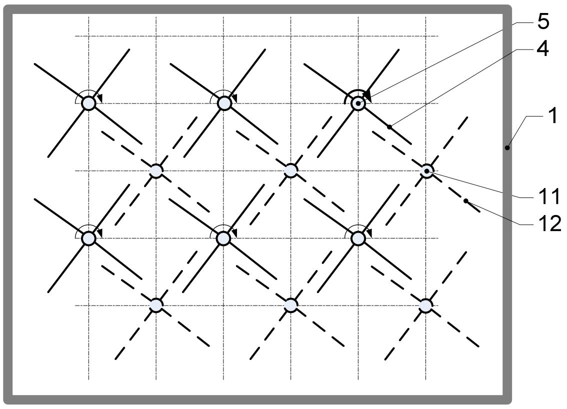

Fig. 6 Mesh electrodes for large cross-section devices

The polluted stream may be introduced and evacuated from the cleaning device at arbitrary, preferably opposite points. For instance, it may be induced from the upper part and disposed of from the bottom, or induced from one side and evacuated from the other side of the duct. It is also understood that the discharge gap may be formed by metal electrodes or metal electrodes with a dielectric coating, preferably ceramics, as in silent discharge devices, or any combinations of the above. The HVPS driving the discharge may be a DC, or pulsed voltage or superposition of the above [12].

3 EXPECTED RESULTS, CRITERIA AND BENEFITS

Focusing on plasma chemistry applications, we expect HEDGe devices to yield removal efficiency close to that of nanosecond PC, based on SO_x/NO_x cleaning results obtained in [7]. More specifically, for NO_x destruction, a removal efficiency of 30-60 gNO_x/kWh without additives, can be expected, similar to our previous results with nanosecond PC [11], [13], [14]. Thus, a $deNO_x$ application, e.g., a small or medium-size diesel engine exhaust cleaning, may be envisaged as base-lining of HEDGe technology. The above figures if achieved can be judged as successful proof-of-concept; they will allow scaling-up the technology for a wide range of pollutants with easily prospected costs. Of course, any other application can also serve for the base-lining.

As an example, consider a larger-scale flue-gas application as outlined in [5], [15]. A 42,000 Nm^3/h stream was cleaned from SOx and NOx with some additives at an energy expense of 1.4 Wh/Nm^3. which corresponds to the useful (reactor) power of 58.8 kW. The pulser power was 120 kW. We have all grounds to believe that without the additives the cleaning efficiency would not be higher than realized in most $deNO_x$ experiments (typically, less than 30 gNO_x/kWh). Therefore, we assume that with additives HEDGe will have the same cleaning effect at the same reactor power of 58.8 kW. With the electrical efficiency of 90 %, typical for DC power supplies, a 65 kW power supply will suffice, with accompanying savings in electricity. Its cost of ~$20,000 is by at least an order of magnitude lower than a 120 kW nanosecond pulser. We note that such pulsers are not available commercially, and the technology is not yet mature for the pollution control market. Thus, the expected benefits are quite sizable.

4 CHALLENGES

It was noted that plasmas at such conditions as depicted in Fig. 1-Fig. 6 were not investigated. First, it should be proven that the discharge power density in the system with revolving electrodes is considerably higher than that of a DC corona. Second, the effectiveness of charging of the particulates should be investigated. Third, the plasma chemistry action must be scaled with the discharge characteristics. However, even with the assumption of good cleaning efficiency, the feasibility of HEDGe technology from the cost considerations is nor self-evident, at least for large scale applications. For, instance, it is a challenge providing high-performance bearings for operation in hostile environments, or high-strength insulators for the electrodes' support.

REFERENCES

1. United States Patent 4,695,358, A. Mizuno and J.S. Clements. Method of removing SO_2, NO_x and particles from gas mixtures using streamer corona. September 22, 1987.
2. V.M. Bystritski, Y.Yankelevich, F. Wassel, et al. Pulsed Power for Advanced Waste Water Remediation. Proc. of 11th IEEE Int. Pulsed Power Conf., Baltimore, June 29-July 2, 1997.
3. W.F.L.M. Hoeben. Pulsed corona-induced degrada-tion of organic materials in water. Ph.D. dissertation, Dept. Physics, Technische Universiteit Eindhoven, 2000.
4. Pokryvailo, A., Wolf, M., Yankelevich, Y., et al. High-Power Pulsed Corona for Treatment of Pollutants in Heterogeneous Media. IEEE Tran-sactions on Plasma Science, Vol. 34, No. 5, 1731-1743, October 2006.
5. Kim, H. H. Nonthermal plasma processing for air-pollution control: A historical review, current issues and future prospects. Plasma Process. Polym. 1(2004), 2, 91-110.
6. United States Patent 4,698,551, Hoag E.D. Discharge electrode for a gas discharge device. March 20, 1986.
7. Yu. S. Akishev, A. A. Deryugin, I.V. Kochetov, A.P. Napartovich and N.I. Trushkin. DC glow discharge in air flow at atmospheric pressure in connection with waste gases treatment. J. Phys. D: Appl. Phys. 1993 (26): 1630-1637.
8. Yu Akishev, M Grushin, I Kochetov, V Karal'nik, A Napartovich and N Trushkin. Negative Corona, Glow and Spark Discharges In Ambient Air and Transitions

Between Them. Plasma Sources Sci. Technol. Vol. 14, 2005, S18–S25.

9. Yu. Akishev, O. Goossens, T. Callebaut et al. The influence of electrode geometry and gas flow on corona-to-glow and glow-to-spark threshold currents in air. [J]. Phys. D: Appl. Phys. 2001 (34): 2875–2882.
10. C. Ren, T. Ma, D. Wang. Stable and diffuse atmospheric pressure glow plasma in a multipoint-to-plane configuration in air. IEEE Transactions on Plasma Science, Vol. 33, No. 1, 210-211, February 2005.
11. Yankelevich, Y., Baksht, R., Wolf, M., Pokryvailo, A., Vinogradov, J., Rivin, B., and Sher, E. NO_x Diesel Exhaust Treatment Using Pulsed Corona Discharge: the Pulse Repetition Rate Effect. Plasma Sources Science and Technology, Vol. 16, 2007, 386–391.
12. H. J. Hall. History of Pulse Energization in Electrostatic Precipitation. Journal of Electrostatics, vol. 25, 1990, 1-22.
13. Pokryvailo, A. and Yankelevich, Y.Sulphur Dioxide Removal from Air Using a High-Power Short Pulsed Corona Discharge. Annual Report of Israel Atomic Energy Commission (IAEC-2000), 2001, 30-62.
14. Yankelevich, Y. and Pokryvailo, A. High-Power Short-Pulsed Corona: Investigation of Electrical Performance, SO2 Removal, and Ozone Generation. IEEE Transactions on Plasma Science, Vol. 30, No. 5, October 2002, 1975-1981.
15. Y. H. Lee, W. S. Jung, Y. R. Choi, J. S. Oh, S. D. Jang, Y. G. Son, M. H. Cho, W. Namkung, D. J. Koh, Y. S. Mok, J. W. Chung. Application of Pulsed Corona Induced Plasma Chemical Process to an Industrial Incinerator. Environ. Sci. Technol. 2003, 37, 2563.