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ROTATING GLIDING ARC: INNOVATIVE SOURCE FOR VOC REMEDIATION

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Abstract. The large-scale plasma treatment of waste gas in industrial or municipal conditions requires high efficiency of plasma conversion process at high processing speed, i.e., large volumetric flow. The integration of the plasma unit into existing systems puts demands on the pipe-system compatibility and minimal pressure drop due to adoption of plasma processing step. These conditions are met at the innovative rotating electrode gliding arc plasma unit described in this article. The system consists of propeller-shaped high voltage electrode inside grounded metallic tube. The design of HV electrode eliminates the pressure drop inside the air system, contrary the plasma unit itself is capable of driving the waste gas at volumetric flow up to 300 m^3/hr for 20 cm pipe diameter. In the article the first results on pilot study of waste air treatment will be given for selected volatile organic compounds together with basic characteristic of the plasma unit used.

Keywords: gliding arc, rotating electrode, waste gas, VOC decomposition, plasma diagnostics.

1. Introduction

The electric arc discharge [1] represents the very basic electric discharge. However, its electrode lifetime is limited as the highly energetic arc plasma causes significant heating/erosion of the electrodes. To reduce the these adverse effects various methods of forced arc channel motion were invented (e.g., [2], to name one of them). One of the modification of arc discharge forcing the arc to move is so-called 'gliding arc' [3, 4], which is studied due to its favourable properties given by transient nature of this plasma source consisting of both thermal equilibrium and thermal non-equilibrium plasma [5–7].

The original invention of gliding arc used horn electrodes design, where the inter-electrode distance was gradually increased and the gas flow along the electrodes' axis forces the arc channel to 'glide'along the electrodes, while extending the channel length leading finally to discharge extinction [3]. This classic way of arc gliding enforcement, which utilizes dragging of arc channel using gas flow, could be used for plasma treatment of the gas stream. However the nozzle used to generate the gas stream could represent a gas flow bottleneck, which limits the amount of gas to be treated and requires a high pressure of the gas on the nozzle entry. The research on the utilization of gliding arc for gas treatment lead to invention of several discharge designs, where the discharge distribution could be further shaped by e.g. the rotation of conical electrode [8] or creation of gas vortex in discharge chamber [9, 10].

However, there exists the other approach of dragging the arc using the motion of electrodes themselves, resulting in changing the effective electrode distance (arc length), in combination with active transport and vectoring the gas stream to plasma region using the propeller-shaped discharge electrode. This originates the invention of 'rotating gliding arc' plasma source [11, 12], which is suitable for large-scale plasma treatment of gasses, or powders.

In our contribution the results of waste gas decontamination studies performed on the volatile organic compounds model species will be presented together with the results of discharge diagnostics.

2. Experimental

For the experiments the rotating electrode gliding arc plasma unit (RGA) was used, see Figs. 1 and 2. The treatment chamber (see Fig. 3) composed of closed-loop pipe system was constructed for controlled waste air plasma treatment experiments. The chamber was equipped with the diagnostics ports and the pumping system for the cleaning of the chamber and control of the gas composition. The RGA unit compose of the specially crafted high-voltage electrode setup of the propeller shape and high-voltage power supply. For pilot experiments the 5-blade axial blower (made of metal) was adapted to serve as the HV electrode and the grounded electrode was made of metallic pipe of 20 cm in diameter. The HV electrode was driven at the 700–1400 rpm, resulting in the peripheral velocity of the blade edge of approx. 7–14 $m.s^{-1}$. With this

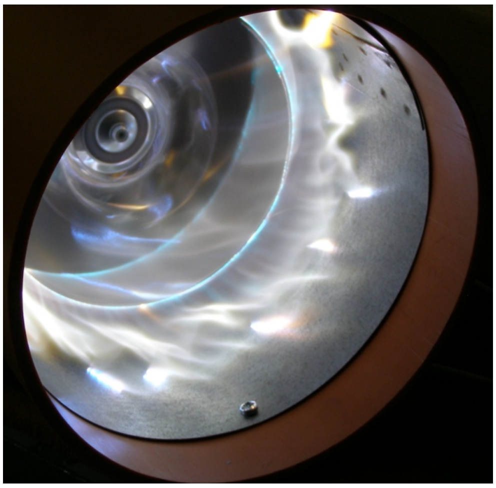

Figure 1. The RGA in operation.

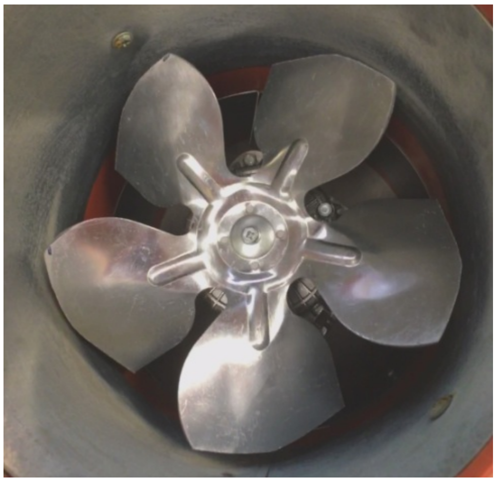

Figure 2. The propeller-shaped electrode system.

setup the 'self-propelled' volumetric flow of waste gas through the RGA unit tops at approx. 300 m^3/hr. The HV electrode was powered with HV power supply, that is capable to deliver up to 1.5 kW peak power at 1–10 kV voltage amplitude, with frequency ranging from 50 Hz to 50 kHz. See experimental setup on Fig. 4.

For the diagnostics the two groups of techniques were used: i) the plasma diagnostics, consisting of fast-framing camera, spectrometer and digital storage oscilloscope, and ii) the gas analysis system consisting of gas chromatography system and gas analyser.

For the analysis of the gliding arc channels the fast-framing camera Photron FASTCAM SA-X2 type 1000K-M2 equipped with Nikkor 180/2.8 lens stopped to f/8 was used. The optical resolution of the camera was approx. 0.2 mm, base on the optical setup and the camera resolution (1024x1024 px). The plasma treatment process was monitored using optical emission spectroscopy, the portable spectrometer Avantes AvaSpec-ULS3648TEC with fixed grating (200–1100 nm), slit width of 25 µm and mean spectral resolution of 1.4 nm was used. The electrical parameters were recorded using digital storage oscilloscope LeCroy WaveRunner 6100A with HV-probe Tektronix P6015A and current monitor Pearson 2877 probe.

For the waste air simulation, the controlled contamination of volatile organic compounds (VOCs), such as toluene ($C_6H_5CH_3$) or acetone (CH_3COCH_3) was introduced to the closed loop of the chamber and RGA plasma treated in several short plasma exposures. The residual contamination analysis was performed using photoacoustic gas monitor Innova 1412i (LumaSense Technologies) and gas chromatograph Agilent 7890B connected with flame ionization detector and quadrupole mass spectrometer Agilent 5977A (Agilent Technologies).

3. Results and Discussion

The aim of the rotating electrode gliding arc development was the inclusion of the plasma decomposition unit into existing waste gas systems with minimal

Figure 3. The closed-loop decontamination chamber.

additional cost and high remediation efficiency. The design of axial ventilator as a self-propelling electrode was proven successful, as the inner tube diameter of 20 cm was sufficient for 300 m^3/hr gas throughput (and prototypes with more than 30 cm diameter were tested with up to 1000 m^3/hr gas throughput). For the gas remediation efficiency test the closed-loop system was used. To follow the plasma decomposition dynamics the plasma was operated in burst mode with effective plasma exposure time of 3 s during each burst and the treated gas was regularly sampled after each burst. The typical result of the plasma treatment is given in Fig. 5. The graph shows the reduction of pollutant present in treated gas in relative units (percent). It can be seen that the plasma decomposition to less than 30% of initial pollutant contamination was achieved in 3 s of plasma operation. After another 3 s of plasma operation the reduction of pollutant

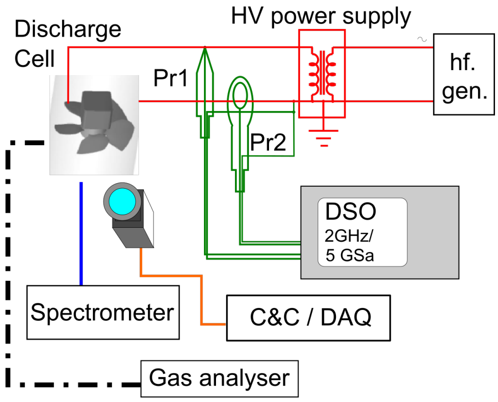

Figure 4. The experimental setup diagram.

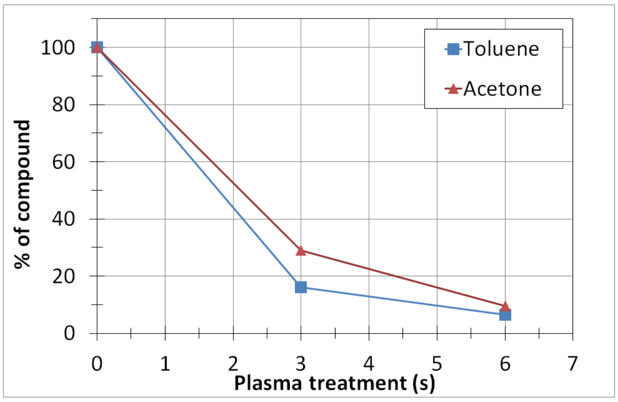

Figure 5. The results on plasma remediation of polluted gas for high initial concentration VOC removal ($5200\,\mu m/m^3$ for toluene and $990\,\mu m/m^3$ for acetone) at 1.2 kW input power at 50 kHz frequency.

reached more than 90%. For these results we have to note, that the reduction was performed on rather high initial concentration of $5200\,\mu m/m^3$ for toluene and $990\,\mu m/m^3$ for acetone.

We have seen, that the plasma remediation efficiency was dependent on the input power to the RGA unit and the efficiency increases with increasing input power. In order to follow the changes in discharge parameters the plasma diagnostics was performed. The discharge structure was observed using fast camera at approx. 2× the input voltage frequency. With this setup we were able to follow the evolution of the discharge channel in subsequent half-periods, but we were not able not follow the single channel evolution within the single half-period of the discharge due to limited frame rate of the camera used. The RGA plasma consists of a bright plasma channel between the HV and grounded electrode. This narrow plasma channel is connecting the edge of propeller HV electrode blade and some point at the surface of outer grounded electrode, see Fig. 6. The plasma channel is periodically reignited between the points of connection, similar to classic horn electrode design [13]. However, in RGA design there is no need to introduce the additional gas flow through the narrow nozzle of gas input to force the arc to glide along the electrodes. This results in low pressure drop in the RGA unit, beneficial to proposed industrial application.

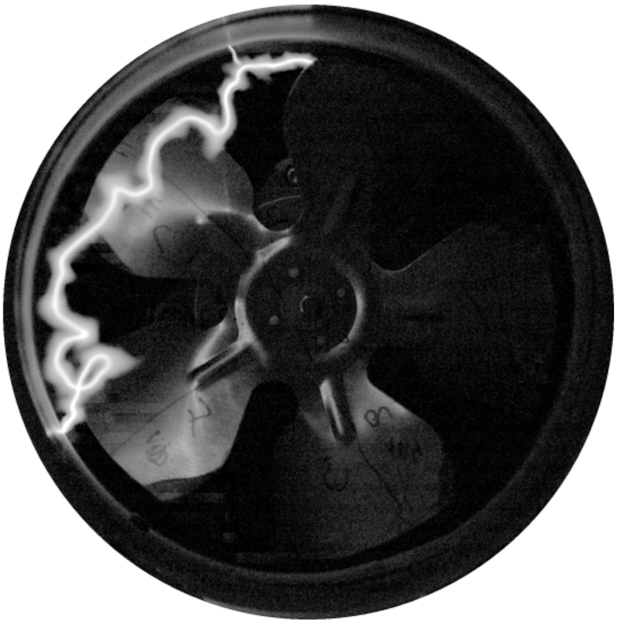

Figure 6. The fast camera image of RGA plasma channel input power of 1500 W and 5 kHz operational frequency.

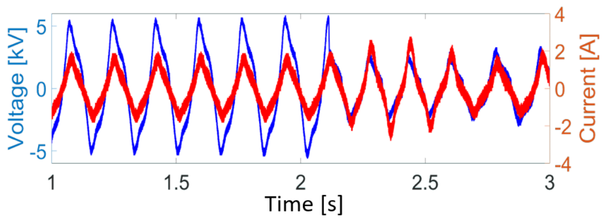

Figure 7. The current-voltage (VA) waveforms of the RGA unit operated at input power of 1500 W and 5 kHz operational frequency.

The discharge channels once ignited evolves in time being stretched by the rotation of HV electrode and the gas flow in the RGA unit. We have seen only a single plasma channel being ignited between the edge of HV blade electrode and outer grounded electrode during a single half-period of input voltage. As the plasma channel is dragged by the rotating HV electrode the length of plasma channel increases and the shape of the plasma channel becomes distorted as the result of turbulent gas flow drag in the direction perpendicular to electrode motion. As the channel evolves the contact point of the plasma channel at outer electrode also evolves and slowly moves in the same direction as the HV electrode. The plasma channel collapses when the input power is no longer sufficient to maintain the discharge (energy losses) or when the channel touches the grounded outer electrode. When the input power is increased the channel length increases and the plasma channel could undergo a series of hops, where the new connection point is established at the surface of outer electrode prolonging the lifetime of plasma channel. As the channel length is correlated with the channel lifetime, the longer the channel is and the longer it can hop in the discharge zone, the longer the effective plasma treatment of the gas will be sustained.

The typical current-voltage (VA) characteristics is given in Fig. 7 for the 1.5 kW input power at 50 kHz frequency. The sudden drop in the amplitude of the voltage could be attributed to the ignition of the discharge. The typical emission spectrum of the discharge consists of highly intense emission from the cathode fall region, where the discharge contacts the electrodes. There the emission of the atomic lines of iron, zinc and aluminium lines were identified, indicating hot spots at the electrodes. The plasma diagnostics was able to give us insight into the changes of plasma channel parameters with respect to outer conditions and to tailor the discharge towards optimal operating conditions and also to modify the design of electrodes in order to optimize the gas flow inside the plasma region.

The last key parameter of RGA unit was the durability of the system. Especially considering the harsh conditions of plasma operation in potentially corrosive environment of treated waste gas and the reactivity of created plasma species, or potentially even the remediation products. For this purpose the long-term stress-tests of the RGA plasma unit were performed. We have checked the condition of the plasma unit after assembly and after the RGA unit was exposed to corrosive environment. Even after 1000 hours in corrosive environment the RGA units does evidence significant degradation, which indicates its potential for real industrial application.

4. Conclusions

The novel design of gliding arc plasma source was constructed and tested for the environmental application of waste air pollution reduction. The advantage of propeller-shaped rotating electrode design proved to be efficient in waste air pollution removal. Devices based on rotating electrode gliding arc technology (RGA) were developed in the laboratories of CEPLANT center and they were applied for the tests of the efficiency of decomposition of selected model VOCs (acetone and toluene) in large volumes of polluted air (hundreds or thousands of m^3/hr). As the final decomposition products, only H_2O and CO_2 were detected in quantifiable amounts.

The RGA plasma cleaning technology of VOCs contaminated air is advantageous for its low operating costs, and intrinsic compatibility with commonly used ventilation systems and also with some other decontamination techniques. The peak reduction of high concentration contaminants was more than 90% in less than 6 second, which means concentration reduction from 5200 $\mu m/m^3$ of toluene, resp. 990 $\mu m/m^3$ of acetone, to less than 350 $\mu m/m^3$ of toluene, resp. 95 $\mu m/m^3$ of acetone. The RGA plasma unit proved to be compatible with existing waste gas pipe systems, regarding the minimal pressure drop due to active gas transport in RGA unit and the scalability of the RGA system (tube diameter, possibility of tandem work, etc.). We have performed also the plasma diagnostics which shows the correlation of contamination removal efficiency using the gliding arc with the discharge occupied area/the channel lifetime. The RGA unit and its applications were patent protected (CZ patent No. 2015 - 310 A3).

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References

[1] Y. P. Raizer. *Gas Discharge Physics*. Berlin: Springer Verlag, 1991.

[2] S. D. Raezer. Arc apparatus employing three dimensional arc motion and dynamic balancing, 1966. Patent No.: US 3,416,021.

[3] H. Lesueur, A. Czernichowski, and J. Chapelle. Dispositif de génération de plasmas basse température par formation de décharges électriques glissantes, 1988. Patent No.: FR 2639172.

[4] H. Lesueur, A. Czernichowski, and J. Chapelle. Électro-brûleurs à arcs glissants. *Journal de Physique Colloques*, 51(C5):C5–57–C5–64, 1990. doi:10.1051/jphyscol:1990508.

[5] A. Fridman, S. Nester, L. Kennedy, A. Saveliev, and O. Mutaf-Yardimci. Gliding arc gas discharge. *Progress in Energy and Combustion Science*, 25(2):211–231, 1999. doi:10.1016/S0360-1285(98)00021-5.

[6] A. Czernichowski. Gliding arc: Applications to engineering and environment control. *Pure and Applied Chemistry*, 66(6):1301–1310, 1994. doi:10.1351/pac199466061301.

[7] F. Richard, J. M. Cormier, S. Pellerin, and J. Chapelle. Physical study of a gliding arc discharge. *Journal of Applied Physics*, 79(5):2245–2250, 1996. doi:10.1063/1.361188.

[8] T. Ombrello, X. Qin, Y. Ju, A. Gutsol, A. Fridman, and C. Carter. Combustion enhancement via stabilized piecewise nonequilibrium gliding arc plasma discharge. *AIAA Journal*, 44(1):142–150, 2006. doi:10.2514/1.17018.

[9] M. McNall and S. Coulombe. Characterization of a rotating gliding arc in argon at atmospheric pressure. *Journal of Physics D: Applied Physics*, 51(44):445203, 2018. doi:10.1088/1361-6463/aade44.

[10] M. Ramakers, J. A. Medrano, G. Trenchev, F. Gallucci, and A. Bogaerts. Revealing the arc dynamics in a gliding arc plasmatron: a better insight to improve CO_2 conversion. *Plasma Sources Science and Technology*, 26(12):125002, 2017. doi:10.1088/1361-6595/aa9531.

[11] P. Stahel, Z. Navratil, M. Zemanek, and M. Cernak. A method of generating low-temperature plasma, a method of plasma modification of liquid, powder, and solid materials with this low-temperature plasma, and a device for carrying out these methods, 2016. Patent application No.: WO2016177353A1.

[12] P. Stahel, Z. Navratil, M. Cernak, and M. Zemanek. Method of generating low-temperature plasma, plasma treatment process of fluids, powder materials and solid substances by making use of such low-temperature plasma and apparatus for making the same, 2015. Patent No.: CZ2015310A3.

[13] L. Potočňáková, J. Šperka, P. Zikán, J. J. W. A. Van Loon, J. Beckers, and V. Kudrle. Experimental study of gliding arc plasma channel motion: buoyancy and gas flow phenomena under normal and hypergravity conditions. *Plasma Sources Science and Technology*, 26(4):045014, 2017. doi:10.1088/1361-6595/aa5ee8.