



Scaling Up of Non-Thermal Gliding Arc Plasma Systems for Industrial Applications

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Abstract

Scaling up of transitional “warm” plasmas to industrial level gives possibility to develop plasma systems that combine advantages of thermal and non thermal discharges such as low temperature and high process selectivity (compare to thermal plasma) at high pressure and average power density. Non-equilibrium “cold” gliding arcs (with observation of equilibrium to non equilibrium transition) has been demonstrated at power level 2–3 kW and proved to be a highly efficient plasma stimulators of several plasma chemical and plasma catalytic processes, including hydrogen/syngas generation from biomass, coal and organic wastes, exhaust gas cleaning, fuel desulfurization and water cleaning from emerging contaminants. The gliding arc evolution includes initial micro-arc phase with fast transition to transient non-equilibrium phase with elevated electric field, low gas and high electron temperatures, as well as selective generation of active species typical for cold plasmas. The paper will describe experimentally achieved scaling up of the non-equilibrium gliding arc discharges to the level of 10–15 kW, as well as theoretical scaling up limitations of this powerful non-equilibrium plasma systems.

Keywords Gliding arc plasmatron · Scaling up · Non-thermal discharges · Non equilibrium transition · Plasma technologies

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Introduction: Scaling Up Challenges of Non-Thermal Plasma Systems, Concept of the Transitional “Warm” Plasmas: Microwaves and Gliding Arcs

The most powerful (up to 100–300 MW) large-scale industrial plasma applications were historically related to thermal plasmas starting with Birkeland–Eyde nitrogen fixation and Huls/Kvaerner natural gas reforming, and coming to modern plasma technologies of melting, powder production and spraying, as well as space-shuttle reentry simulation [1–3].

From the perspectives of plasma physics, the ability of thermal plasma to be scaled up to enormous power level is due to its ionization-overheating stability with respect to perturbations of temperature, density, and reduced electric field. From engineering perspective, however, the thermal plasma systems with temperatures exceeding 3000–5000 K have significant drawbacks related to very high energy losses and electric energy consumption, as well as material problems limiting lifetime of electrodes and the whole system.

Use of non-thermal plasma systems permits to overcome the above-mentioned energy cost and material challenges because of low gas temperature and high selectivity (compare to thermal plasma) of the non-equilibrium plasma processes (energy efficiency and selectivity up to 80–90%). It explains wide range of successful non-thermal plasma applications in microelectronics, polymer treatment, ozone generation, plasma assisted ignition and combustion, etc. [4, 5]. Scaling up of the non-thermal plasma systems to high power, pressure, and production level is limited, however, by the plasma instabilities with respect to perturbations of temperature, density, and reduced electric field. Relevant non-thermal plasma stabilization usually leads to restrictions of operational pressure (to the level of Torr or mTorr) or average power density of the systems (to the level below Watts per cm^3). As a result, the most powerful and productive continuous non-thermal plasma systems, industrial ozone generators, have power up to 100–300 kW (still 3 orders of magnitude below the most powerful arcs), and characterized by large sizes (exceeding those of thermal plasma systems at least 3–4 orders of magnitude).

Combining advantages of thermal and non-thermal plasma systems for industrial scaling up (low temperature and high process selectivity at high pressure and average power density) becomes possible by using of the so-called transitional plasma of “warm” discharges, like moderate pressure (100–200 Torr) microwave discharges and non-equilibrium gliding arc discharges [6–10]. Instead of suppressing the ionization-overheating instabilities, these discharges operate in the regimes unstable in-space or in-time. All the transitional “warm” discharges have areas or phases with relatively high electric field (3–10 Td; for comparison—in hot thermal arcs Td is in the range 0.03–0.3), relatively low gas temperature (300–1000 K), and physically combine in space or in time both thermal and non-thermal ionization mechanisms. Physics-wise, the moderate pressure microwave discharges operate, in the space non-uniform regime with a high-temperature (2000–3000 K) central filament reflecting majority of microwave energy because of skin-effect, and low temperature (300–1000 K) surrounding where most of energy is absorbed. Gas temperature of “warm” plasmas is very convenient, for example, for fuel conversion and biomass gasification as well as for pyrogas reforming. It is in the range of the typical temperatures of these chemical processes. In that case radicals and other active plasma species have rather long lifetime to cause catalytic effect (so-called plasma catalysis). These plasmas are powerful enough to provide fast start and short transient time, do not imply additional limitations on the thermal insulation of the process, and do not cause soot formation as thermal plasmas. Though some groups are trying to use microwave plasma for fuel conversion [9], most of

groups involved in this technology (at least in the USA) decided to use different types of gliding arc because of the discharge simplicity and stability of electrodes [10].

Industrial application of non-equilibrium “warm” plasma systems was demonstrated in the case of microwaves on the power level up to 1 MW, with possible further scaling up. This paper is focused on scaling up of the non-equilibrium gliding arcs, which also operates without suppressing the ionization-overheating instabilities, in time-periodic and time-non-uniform regime. The gliding arc evolution includes initial micro-arc phase with fast transition to transient non-equilibrium phase with elevated electric field, low gas and high electron temperatures, as well as selective generation of active species typical for cold plasmas. The paper will describe experimentally achieved scaling up of the non-equilibrium gliding arc discharges to the level of 10–15 kW, as well as theoretical scaling up limitations of this powerful non-equilibrium plasma systems.

Gliding Arcs: Equilibrium vs. Non-Equilibrium Phases

Over last several years the researchers at Drexel Plasma Institute developed a range of non-thermal gliding arc plasma processes for syngas production from almost any kind of hydrocarbon feedstock, including natural gas, diesel, glycerol, gasoline, JP8, solid biomass and heavy oils.

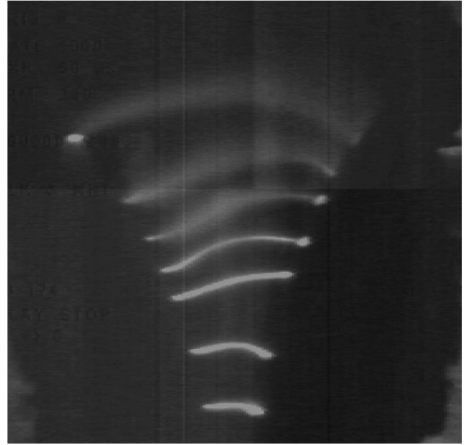
The key feature of gliding arc reforming process is that non equilibrium plasma used only as a catalyst thus ensuring minimum energy consumption (1–2% of fuel heating value). The best application of gliding arc is when the process is exothermal or autothermal (for example fuel partial oxidation or fuel air steam reforming) or reacting gas is already preheated (for example exhaust gas of municipal wastes gasification).

Some of the main advantages of gliding arc plasma discharge includes its ability to achieve high power (up to 10–15 kW in a single unit) for high reactor productivity as well as maintaining a high degree of non-equilibrium to sustain a selective chemical process.

Effective non equilibrium operation of gliding arc requires cold secondary electron emission mechanism of providing electrons to the gliding non equilibrium arc channel. Non equilibrium regime is limited by transition from cold secondary electron emission to hot and highly erosive thermionic emission taking place at elevated currents and powers. Identification of maximum current level (and related levels of plasma power) preventing transition to thermionic emission at different arc motion modes further discussed in this paper.

The conventional “flat” gliding arc (Fig. 1) starts as an electrical breakdown in a narrow gap between two or more diverging electrodes in a gas flow. When the electric field in this gap reaches approximately 3 kV/mm in air at normal conditions, current of the arc increases very fast and voltage on the arc drops. If the gas flow is strong enough, it forces the arc to move along the diverging electrodes and to elongate. The growing arc demands more power to sustain itself. At the moment when its resistance becomes equal to the total external resistance, the discharge consumes one half of the power delivered by the power supply. This is the maximum power that can be transferred to the arc from the constant voltage power supply with a serial resistor. Taking into account that thermal arcs consume energy proportionally to their length and are independent on a wide range of current variation, one can conclude that GA should not sustain elongation beyond this “critical point”. Experimental and theoretical studies [7] show that in some cases the gliding arc *can* elongate further (so-called “overshooting effect”), because it

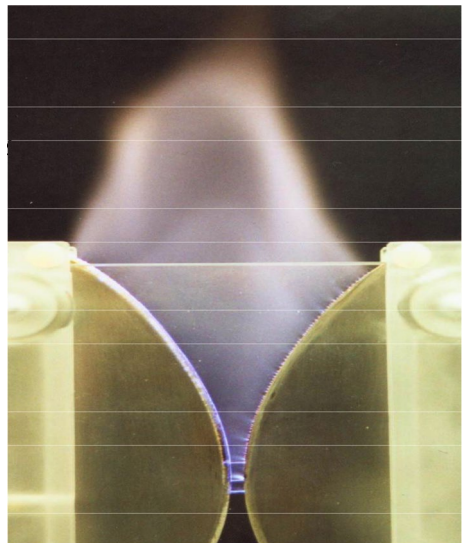
Fig. 1 Gliding arc evolution shown with 5 ms separation between snap shots



becomes non-equilibrium in the vicinity of the critical point, and the non-equilibrium discharge consumes less energy with current reduction. Also, in contrast to the thermal arcs cooled predominantly by conductive heat transfer, non-equilibrium discharge is “ventilated” by dragging flow (convective cooling), and becomes wider and less bright (Fig. 2).

A gliding arc has big advantages from the point of view of simplicity and energy efficiency [11]. At the same time, early designs had poor fuel conversion efficiency because a 2D configuration results in a large amount of reacting mixture just passing through without contact with the gliding arc.

Fig. 2 Gliding arc discharge



Flat vs. Reverse Vortex Gliding Arcs, Engineering Robustness for Industrial Applications

An improved system for plasma reforming of liquid and gaseous hydrocarbons has been developed at Drexel Plasma Institute, based on gliding arc direct and reverse vortex design, which incorporate design features that are adequate for industrial use [12–14]. A schematic of developed Gliding Arc Plasmatron is presented in Fig. 3.

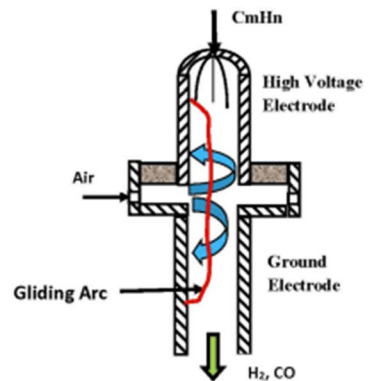
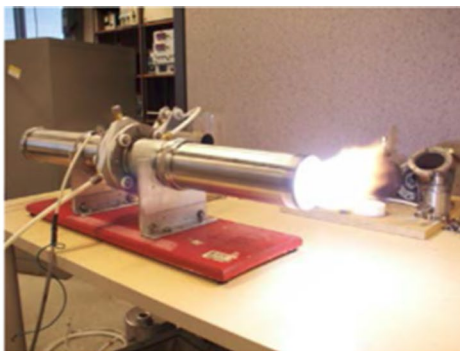
Novel design of Gliding Arc Plasmatron consists of high voltage cylindrical electrode, electrical insulator, and ground cylindrical electrode with tangential inlet holes.

Plasma gas (Air or Air in mixture with steam) enters the cylindrical reactor through tangential inlet holes. Gliding arc discharge starts in the gap between 2 electrodes and stretches both ways (upward and downward) by incoming gas vortex. At the same time gliding arc rapidly rotates thus creating “quasi-volumetric” plasma zone. Liquid or gaseous hydrocarbon fuel such as natural gas, biodiesel, glycerol etc. enters plasma zone where different chemical reactions occurs.

Compare to flat gliding arc this design has advantages of high energy and conversion efficiency, very long (practically unlimited) stainless steel electrodes life time, robustness and simplicity that are very compatible to industry requirements. Also due to its robustness the gliding arc plasmatron can operate at different conditions, for example in high temperature exhaust gas atmosphere or be submerged into the water during plasma treatment process.

Observation of Electric Field Evolution in Gliding Arcs: Transition from Equilibrium to Non-Equilibrium Phases in Flat and Reverse Vortex Gliding Arcs

Non equilibrium gliding arcs described in the “[Gliding Arcs: Equilibrium vs. Non-Equilibrium Phases](#)” section are possible only if reduced electric field in the critical point jumps to values above 3 Td sufficient to sustain non equilibrium “cold” ionization [15].



Operational 10 kW Gliding Arc Plasmatron

Fig. 3 Schematic and operational gliding arc plasmatron

Fig. 4 A typical current–voltage oscillogram of gliding arc. Flow rate is 330 SLM¹⁵

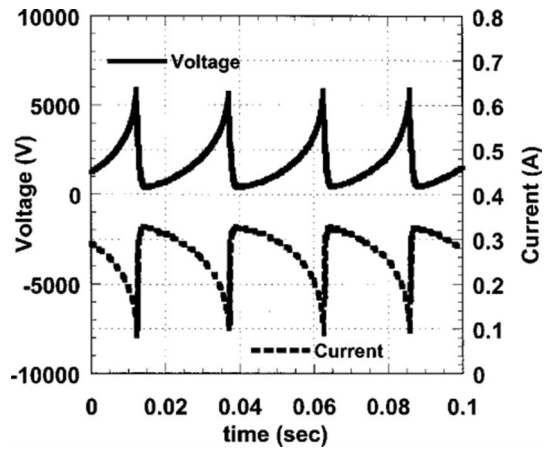
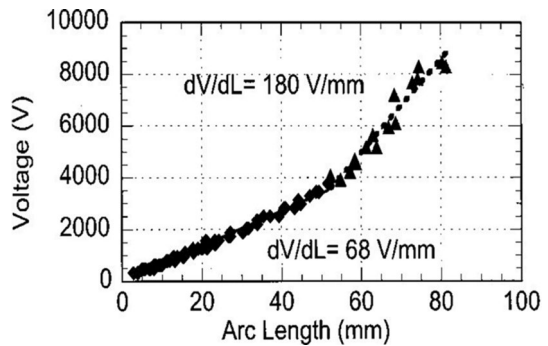


Fig. 5 Time average voltage–discharge length characteristics of a gliding transition discharge¹⁵



The histogram in Fig. 4 shows the correlation between current and voltage throughout arc evolution. The voltage increases along with the discharge length whereas the power remains constant.

Power per unit length ($E \cdot I$) remains almost constant during initial phase of gliding arc development. Therefore the required minimum level of electric field results in limitation of maximum gliding arc current value. If initial current is too high, the reduced electric field in the critical point remains below 3 Td and thermal gliding arc channel simply extinguishes without transition to non equilibrium.

This effect of the maximum allowed current and power per unit length is crucial for scaling up of non equilibrium gliding arc.

Finding the maximum arc current and voltage where the nonequilibrium mode of gliding arc operation is still exists defines the power of single plasma unit for specific operational parameters and plasmatron inner geometry. The equilibrium- to- non- equilibrium transition point can be observed experimentally as an abrupt change of electric field found as dV/dL derivative of voltage dependence on arc channel length. This relatively simple approach demonstrated first for flat gliding arc (see Fig. 5) [15] is in a good agreement with detailed spectroscopic temperature measurements before and after transition [16]. The employed measurement techniques combined continuous recording of discharge column evolution by a high-speed video camera ~ up to 1000 frames per second and synchronized

time average current–voltage measurements, which is relatively easy to achieve in a flat 2D gliding arc configuration. In order to obtain the time-resolved length and position diagnostics of the moving plasma channel, digitally stored images were subsequently analyzed in a personal computer by using a image processing and analysis software (Image Analyst™, AM 3300).

The power per unit length level at which the transition to non equilibrium has been observed in these experiments was 0.1–0.2 kW/cm corresponding to currents not exceeding ~ 1 A [15].

In this paper, we applied the same approach to find out the maximum value of current and power per unit length for 3 D gliding arc discharges stabilized in direct vortex flow.

Since the observation of the gliding arc movement inside the gliding arc plasmatron (Fig. 3) is limited it’s been assumed that the gliding arc length is directly proportional to the plasma gas flow rate. In this case the dependence of the gliding arc voltage on plasma gas flow rate should show the same transition from equilibrium to non equilibrium mode as in Fig. 5 for flat 2 D gliding arc.

Characteristics of the direct vortex gliding arc plasmatron were studied experimentally in wide range of plasma gas (air)—200–1200 LPM and plasma current 1–8 A. Inner diameter of GA plasmatron was 3.5" and length of high voltage and ground electrodes — 18".

The experimental results (Fig. 6) show the same correlation between changing in time average voltage increase rate and air flow rates at low and moderate currents (1–2 A) as in the case of 2D flat gliding arc (Fig. 5). In the case of flat 2D gliding arc the sudden break in dV/dL was related to transition from non equilibrium to equilibrium regimes, which was confirmed by spectroscopic temperature measurements before and after the slope break. In our case the picture 6 shows the same slope break in voltage as air flow rate increases (if our assumption about arc length and air flow rate direct proportionality is correct). At higher plasma current levels (> than 2 A) the gliding arc remains in the equilibrium thermal mode and discharge is supported by thermal ionization.

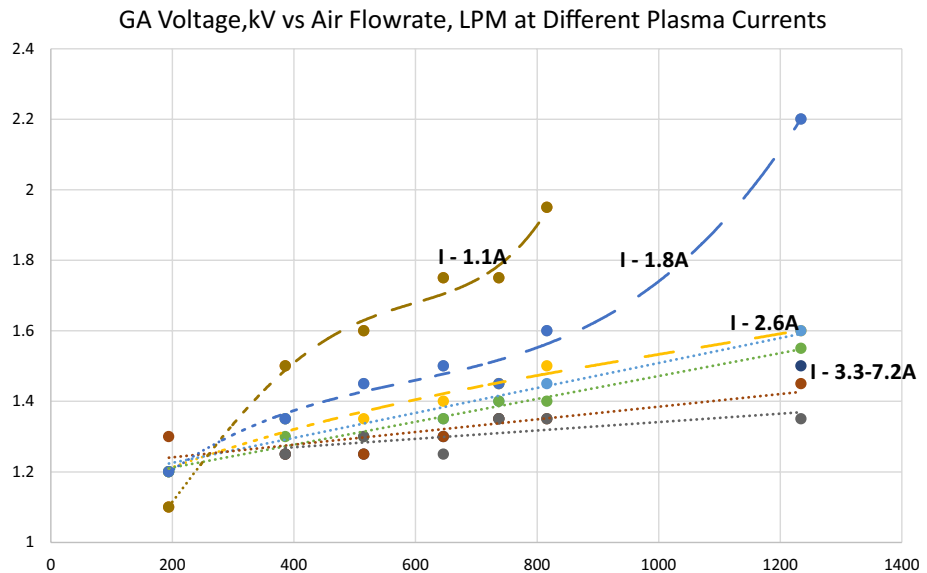


Fig. 6 Dependence of gliding arc voltage (kV) on plasma air flow rates (LPM) at different plasma currents

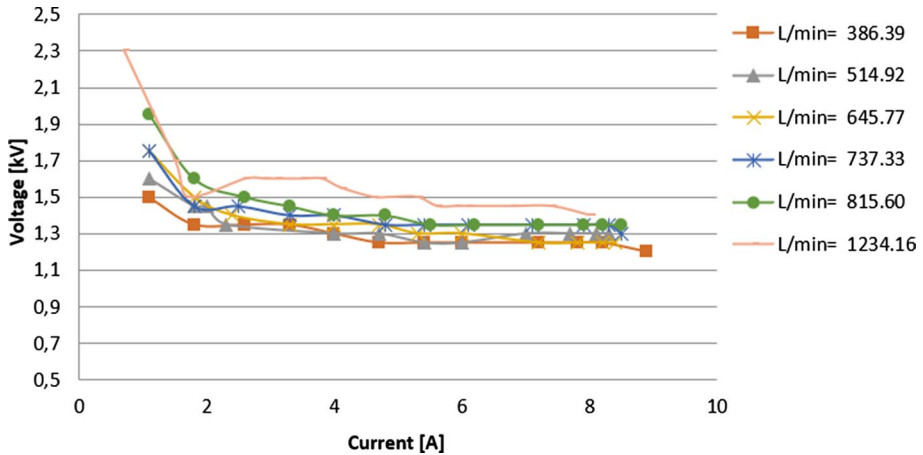


Fig. 7 V-I time average characteristics of GA plasmatron at different air flow rates

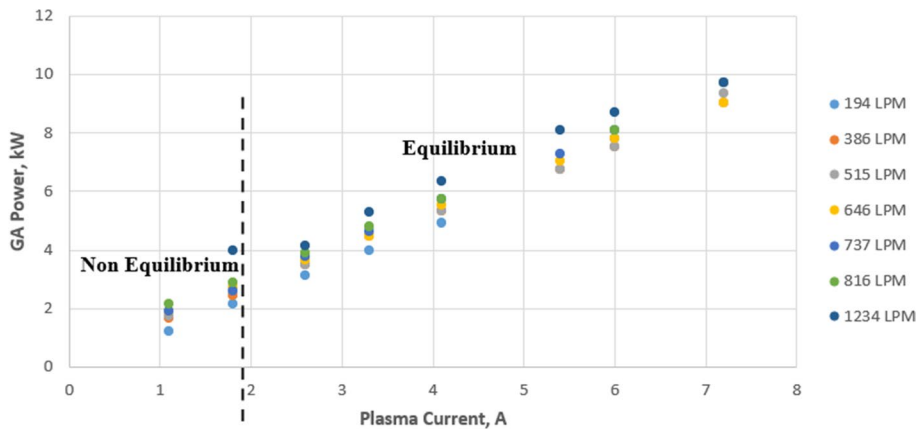


Fig. 8 GA power vs plasma current at different air flow rates

The V-I characteristics of GA plasmatron taken in the range of air flow rates 386–737 LPM also show the break in plasma voltage linearity around 1.5–2 A, corresponding to transition from equilibrium to nonequilibrium regime (Fig. 7).

It is evident from these results that the plasma power of the single GA plasma unit operating in nonequilibrium regime is limited to 2–3 kW (for this specific range of plasma current and plasma gas flow rates) (Fig. 8). After that even although gliding arc plasmatron still has advantages of simplicity, robustness and long electrodes lifetime compare to thermal plasmatrons, it can only be used as a heat source. For maximal tested plasma power level 10–12 kW the produced plasma jet enthalpy could be as high as 0.4–0.8 kWh/m³ (Fig. 9) which correspond to temperature level 1500–2200 K (Fig. 10).

Further increase of gliding arc plasma power can be provided by increase of voltage and special multistage configuration of GAT reactor [17]. Increase of gliding arc voltage (corresponding to arc length) could be achieved in a reverse vortex plasmatron configuration

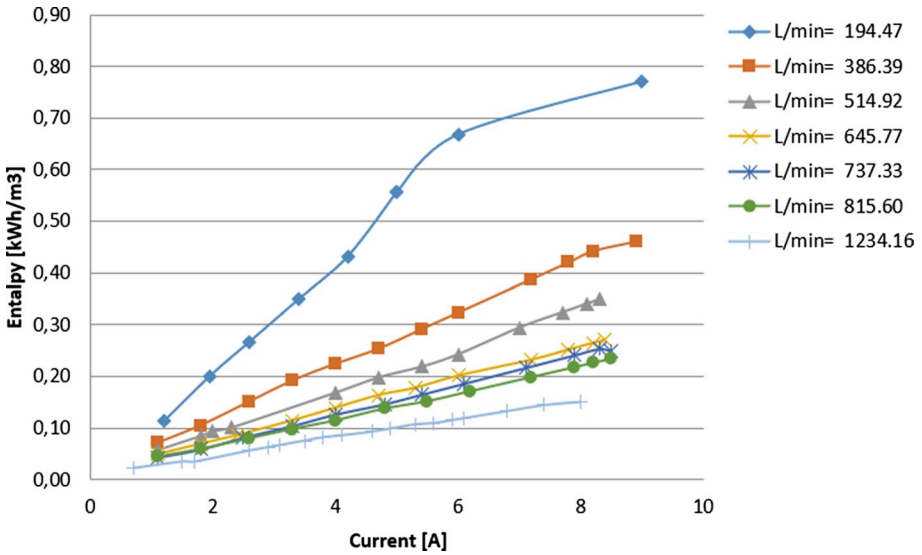


Fig. 9 Enthalpy of plasma jet at different air flow rates

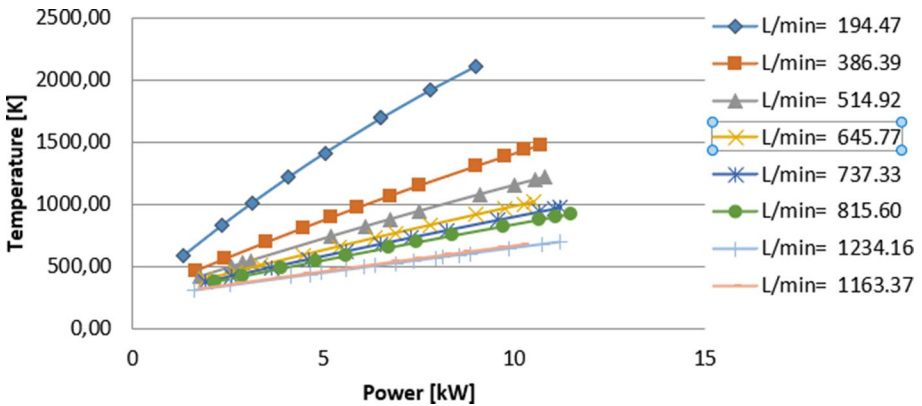


Fig. 10 Gliding arc plasma temperature at different air flow rates

(Fig. 11c). Identification of optimal schemes of combining single plasma units into complex GAT plasma configurations without losing required level of plasma non equilibrium is a subject of future research. Also it is obvious that obtained gliding arc characteristics only relevant to specific gliding arc plasmatron inner geometry and analyzed range of voltage, current and air flow rates. In order to obtain parameters necessary for scale up of plasma system to industrial level further research is required.

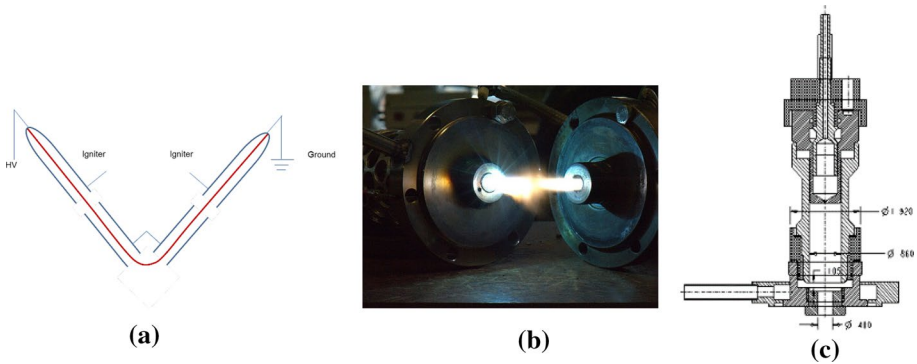


Fig. 11 Different scale up schematics of gliding arc plasmatrons: **a, b** serial connection of gliding arc plasmatrons into one chain; **c** reverse vortex gliding arc plasmatron

Industrial Applications of Gliding Arc

Large scale (up to 10 kW) gliding arc plasma reformer has been developed and installed at municipal wastes gasification plant in Ottawa (Canada). In this reformer, the gliding arc plasma operated in non equilibrium regime at power levels 2–3 kW. At higher powers (3–10 kW), the gliding arc reformer operated close to thermal equilibrium as a heat source. The gliding arc plasma reformer was designed for efficient reforming of high temperature (greater than 650 °C) “dirty” pyrogas containing heavy hydrocarbons, air, and water vapor into clean synthesis gas containing H₂, CO and N₂ [18]. Reformer was installed and continuously operated for several months in high temperature exhaust manifold of municipal waste gasifier (Fig. 12).

As it was mentioned before the big advantage and key feature of gliding arc reforming process is that non equilibrium plasma used only as a catalyst thus ensuring minimum energy consumption (1–2% of fuel heating value). The best application of gliding arc is when the process is exothermal or autothermal (for example fuel partial oxidation or

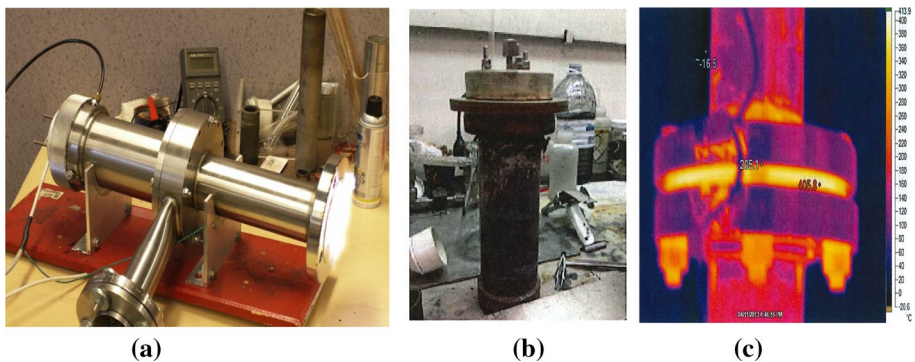


Fig. 12 10 kW gliding arc plasma reformer of high temperature pyrogas: **a** testing of 10 kW GA plasma reformer before installation in exhaust manifold; **b** GA plasma reformer after continuous operation at high temperature (~650 °C) environment; **c** GA plasma reformer during operation in high temperature exhaust manifold

fuel air steam reforming) or reacting gas is already preheated (for example exhaust gas of municipal wastes gasification) (Fig. 13).

Another highly promising area of large scale application of gliding arc plasma systems is production of large quantities of plasma activated water (PAW) used as a fertilizers for agriculture, or for fresh produce sterilization.

We developed 100 L capacity plasma system with submerged 3 kW gliding arc plasma-tron that could be used for PAW production with pH in the range 3–6 and for washing and disinfection of fresh produce [19]. The gliding arc plasma in this system operated in non equilibrium regime with clear observation of equilibrium to non equilibrium transition.

Fig. 13 Production of plasma activated water for agriculture

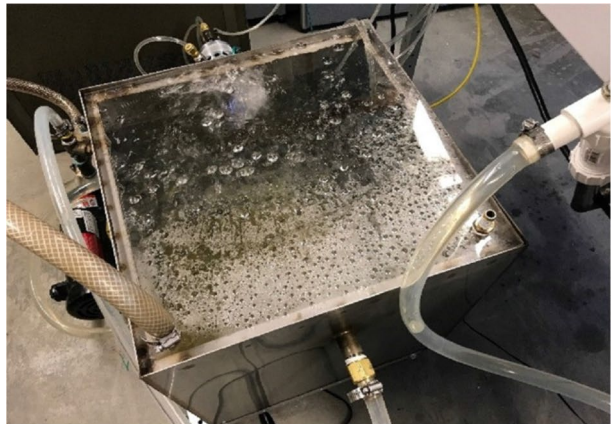


Figure 1. Stainless steel water tub for wash water disinfection by submerged gliding arc plasma.



Figure 3. Modified plasmatron submerged into tub

The gliding arc plasmatron developed at NPI can also be successfully used in large scale applications such as plasma water cleaning from emerging sub-micro contaminants. For example, submerged gliding arc plasmatron, a schematic of which is shown in Fig. 14, is a promising treatment technology for water matrices contaminated with poly- and perfluoroalkyl substances (PFAS), which are a diverse set of organofluorine surfactants that are resistant to degradation by conventional treatment methods. PFAS compounds have been used extensively in a variety of industrial, commercial, and residential products and applications for decades. They have notably been used in newspaper printing, textile and paper production, metal plating, surfactants in fluoropolymer production, and aqueous film-forming foams (AFFFs), and are found in consumer products such as outdoor apparel, dental floss, and car wax. As a result, they have emerged as persistent pollutants in the environment and are commonly found in groundwater, surface water and wastewater. A growing body of evidence suggests that PFAS are bioaccumulative and pose a significant threat to human and ecological health, which has led to US and international PFAS regulations (e.g., USEPA, European Union, several US states). For example, the USEPA recently releasing a drinking water health advisory level for the combined concentration of perfluorooctane sulfonate and perfluorooctanoate (PFOS and PFOA, respectively) at 70 ng/L, the goal of PFAS treatment technologies must be able to achieve low part per trillion (ng/L).

At present, remediation of PFAS is limited to ex situ methods using pump-and-treat systems using granular activated carbon (GAC) or ion exchange (IX) resins. Unfortunately, PFAS captured on GAC or IX resins either need to be disposed of or undergo additional treatment for their regeneration and reuse. Thus, a water treatment technology

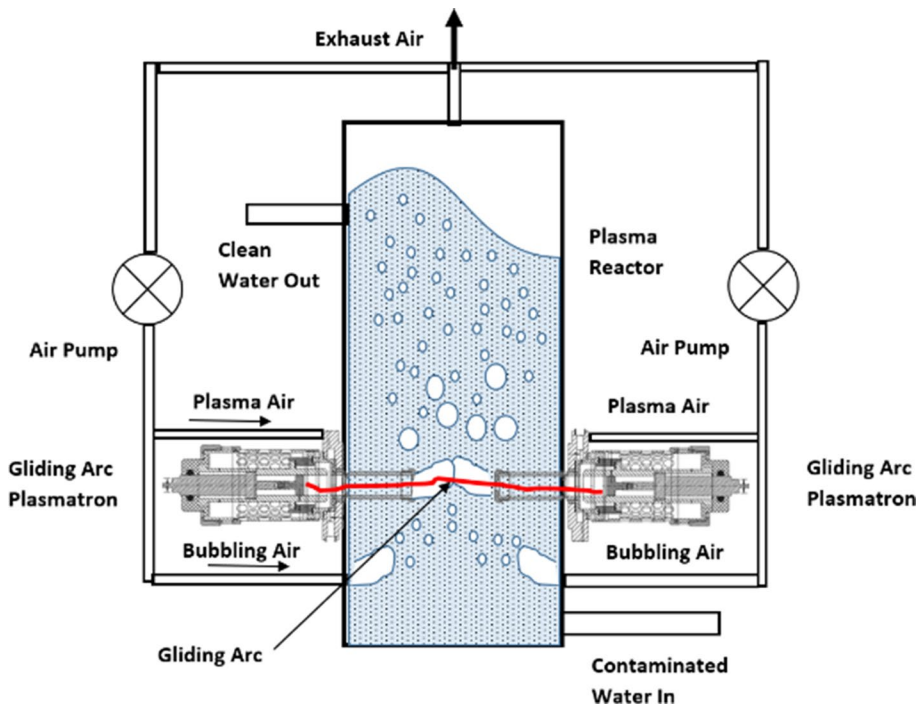


Fig. 14 Water cleaning by submerged gliding arc plasmatron

that effectively and efficiently degrades these compounds has been highly sought after, for example, the U.S. Department of Defense through their Strategic Environmental Research and Development Program (SERDP) and Environment Security Technology Certification Program (ESTCP) (2017) have funded projects aiming at developing novel PFAS treatment technologies. One of these technologies uses corona discharge in Ar gas and was first described in Stratton et al. (2017) to degrade perfluorooctanoic acid (PFOA) and perfluorooctanesulfate (PFOS) in water [22]. Amazing, efforts to scale-up the system from Stratton et al. (2017) have shown initial success in pilot-scale treatment of AFFF contaminated groundwater at approximately 3 gallons per minute (GPM) (per conversations with Selma Mededovic Thagard). However, due to the low maximum power output of a single corona discharge electrode ($\sim 1 \text{ mW/cm}^3$), it would require many of these electrodes in parallel to effectively degrade PFAS at full-scale. GAP plasma technologies, on the other hand, are significantly more powerful, with single electrodes having maximum power outputs of 100,000 and 10,000,000 mW/cm^3 , respectively. These more powerful plasma discharges can create more energetic and reactive conditions with a smaller system footprint, making GAP and DBD more scalable. The reverse vortex flow gliding arc plasmatron (GAP) used in our liquid PFAS treatment systems, for example, has the possibility of being scaled up to industrial level with low energy consumption and adapted for continuous flow treatment of water [23, 24]. GAP electrodes of up to 10 kW have been developed at the Drexel University C&J Nyheim Plasma Institute (NPI) for large-scale applications, such as gaseous and liquid waste treatment, as well as production of plasma activated water for agricultural applications. GAP discharges in air can be highly energetic and produce reactive conditions with UV, heat, and both ROS and reactive nitrogen species (RNS) that could contribute to degradation and destruction of PFAS. In preliminary experiments, it was demonstrated that submerged gliding arc plasmatron is capable of degrading a range of PFAS, including perfluoroalkyl carboxylate (PFCA), perfluoroalkyl sulfonate (PFSA) and fluorotelomer sulfonate (FtS) compounds of varying chain lengths in aqueous solutions [20].

The plasma jet containing active species such as ROS (reactive oxygen species), RNS (reactive nitrogen species), OH radicals and plasma treated droplets injected into the bulk of treated water thus creating intense mixing and efficient removal of PFAS.

Preliminary experiments proved feasibility of approach with removal of at least 90% of PFAS at energy cost on the level of $\sim 20\text{--}30 \text{ kJ/L}$ of treated water which is ~ 10 times cheaper than those of alternative plasma approaches and corresponds to operational cost of the technology below $\$1/\text{m}^3$ of water (which is cheaper and ecologically safer than conventional GAC and ion-exchange technologies). Plasma treated water at the optimal operational gliding arc parameters meets EPA standards (nitrides/nitrates concentration below 1 mg/L , pH above 6) [20].

Physical Limits of the Non-Thermal Gliding Arcs Scaling Up

As it was discussed in the previous “[Observation of Electric Field Evolution in Gliding Arcs: Transition from Equilibrium to Non-Equilibrium Phases in Flat and Reverse Vortex Gliding Arcs](#)” section, the most interesting transitional non-equilibrium gliding arc regime has been demonstrated in our experiments with direct vortex stabilized plasma at the current level about 1.5 A, voltage about 1.5 kV, and power about 2 kW. At higher levels of discharge current and power, the gliding arc transition to the “cold” non-equilibrium mode has not been observed. The fast equilibrium-non-equilibrium transition

(FENETRE) of the discharge has been observed at the arc channel length about 15 cm, corresponding to the plasma power per unit length about 0.15 kW/cm, average electric field about 0.1 kV/cm, and reduced electric field (keeping in mind temperature in the thermal zone about 2000–3000 K) about 3 Td ($3 \times 10^{-17} \text{ V} \times \text{cm}^2$). These data are in good agreement with both experimental data on the FENETRE phenomenon previously observed in flat-geometry gliding arcs [15] and theoretically calculated critical FENETRE parameters [21].

The confirmation of the critical FENETRE parameters in the powerful non-equilibrium gliding arcs stabilized in the reverse-vortex (Tornado) flows, permits to estimate expected physical limits for scaling up of the non-equilibrium “cold” gliding arcs from today’s highest achieved power of 2 kW (the maximum thermal plasma power at the same gliding arc configuration but higher currents goes up to 15 kW):

1. The reduced electric field at the FENETRE transition is now experimentally of about 3 Td ($3 \times 10^{-17} \text{ V} \times \text{cm}^2$). During the further scaling up it should be about 5–7 Td required to sustain the non-thermal ionization [21].
2. Increase of current (from the today’s level of 1.5 A) and therefore power per unit length (from the today’s level of 0.15 kW/cm) is possible without transitioning in completely thermal arc regime only by cooling intensification (partial turbulization) of the arc channel periphery. Such approach [21] permits to approximately *triple of the arc current* and therefore power per unit length to the maximum level of about 5 A and 0.5 kW/cm.
3. The maximum power per unit length of the non-equilibrium “cold” gliding arc is therefore about 0.5 kW/cm, which is 20 times lower than maximum power per unit length of the thermal arc discharges (achieving 10 kW/cm, corresponding to arc channel temperatures of 20,000 K).
4. Maximum power of the non-equilibrium “cold” gliding arc is limited by maximum channel length, which is similarly to thermal arcs are limited today by channel stabilization engineering on the level of about 10 m. It results in the maximum one-unit “cold” gliding arc power on the level of 5 MW. While it is still 20–40 times lower than the maximum one-unit power of thermal arc plasmas (100–200 MW), it is 20–50 times higher than maximum power of the cold plasma systems (100–200 kW) [21].

Conclusion

- Scaling up of gliding arc discharges to power level 10 kW in one unit has been developed and tested in industrial conditions for exhaust gas cleanup of municipal waste gasification plant.
- Non-equilibrium “cold” gliding arcs (with observation of equilibrium to non equilibrium transition) has been demonstrated at power level 2–3 kW and proved to be a highly efficient plasma stimulators of several plasma chemical and plasma catalytic processes, including hydrogen/syngas generation from biomass, coal and organic wastes, exhaust gas cleaning, fuel desulfurization and water cleaning from emerging contaminants.
- Experimental observation of an abrupt change of electric field (similar to one found as dV/dL derivative of voltage dependence on arc channel length for 2D flat arc) demonstrated the maximum current and power per unit length level of non-equilibrium gliding arcs as: 1–2 A and 0.15 kW/cm respectfully.

- Analysis of physical limits of the non thermal gliding arc scaling up shows the maximum expected power per unit length of 0.5 kW/cm and maximum total power on the level of 5 MW in one unit.

Further increase of plasma power required for industrial level while maintaining high chemical selectivity of non equilibrium plasma can be provided by using multimodular schematic where single gliding arc units combined using for example a serial connection (Fig. 12).

References

1. Kaske G, Kerke L, Muller R (1986) Hydrogen production in huls plasma reforming process. *Hydrogen Energy Progress VI*:1
2. Lunum S, Hildrum R, Hox K, Hugbald J (1998) Kvaerner based technologies for environmentally friendly energy and hydrogen production. In: *Proc. 12th world hydrogen energy conference*, Buenos Aires, pp 637–645
3. Fridman A (2008) *Plasma chemistry*. Cambridge University Press, p 978
4. Ombrello T, Qin X, Ju Y, Gutsol A, Fridman A (2005) Enhancement of combustion flame stabilization using stabilized non-equilibrium plasma. In: *43rd AIAA aerospace sciences meeting and exhibit*, AIAA-2005-1194, Reno, Nevada
5. Staack D, Farouk B, Gutsol A, Fridman A (2005) Characterization of a DC atmosphere pressure normal glow discharge. *Plasma Sources Sci Technol* 14(4):700–711
6. Gutsol AF, Zhivotov VK, Potapkin BV, Fridman AA, Rusanov VD (1990) MW discharge in supersonic flows of molecular gases. *Russ J Techn Phys* 60(7):62–70
7. Kuznetsova IV, Kalashnikov NY, Gutsol AF, Fridman AA, Kennedy LA (2002) Effect of “overshooting” in the transitional regimes of the low current gliding arc discharge. *J Appl Phys* 92(8):4231–4237
8. Fridman A, Chirokov A, Gutsol A (2005) Topical review “non thermal atmospheric pressure discharges.” *J Phys D: Appl Phys* 38(2):R1–R4
9. Babaritskii AI, Baranov IE, Bibikov MB, Demkin SA, Zhivotov VK, Konovalov GM, Lysov GV, Moskovskii AS, Rusanov VD, Smirnov RV, Cheban'kov FN (2004) Partial hydrocarbon oxidation processes induced by atmospheric pressure microwave discharge plasma. *High Energy Chem* 38:407–411
10. Kalra CS, Gutsol A, Fridman A (2005) Gliding arc discharge as a source of intermediate plasma for methane partial oxidation. *IEEE Trans Plasma Sci* 33(1):32–41
11. Hartvigsen J, Elangovan S, Czernichowski P, Czernichowski A (2006) Achieving high efficiency in liquid fueled solid oxide fuel cell systems. In: *Presentation on the fuel cell seminar*, Honolulu, pp 21–23
12. Bromberg L, Cohn DR, Rabinovich A (2006) Onboard plasmatron hydrogen production for improved vehicles. MIT Report PSFC JA-06-3
13. Kalra C, Cho Y, Gutsol A, Fridman A, Rafael TS (2004) Non-thermal plasma catalytic conversion of methane to Syn-Gas. In: *Preprint: FUEL 226, the 228th ACS national meeting in Philadelphia*
14. Gallagher MJ, Geiger R, Plevich A, Rabinovich A, Gutsol A, Fridman A (2010) On-board plasma assisted conversion of heavy hydrocarbons into synthesis gas. *Fuel* 89:1187–1192
15. Mutaf-Yardimci O, Saveliev AV, Fridman AA, Kennedy LA (2000) Thermal and nonthermal regimes of gliding arc discharge in air flow. *J Appl Phys* 87(4):1632–1641
16. Czernichowski A, Nassar H, Ranaivosoloarimanana A, Fridman AA, Simek M, Musiol K, Pawelec E, Dittrichova L (1996) *Acta Phys Pol A* 89:595
17. Rabinovich A, Nirenberg G, Chernets I, Fridman A (2015) High power non-thermal plasma system for industrial applications. US Patent 9,216,400
18. Odeyemi F, Rabinovich A, Fridman A (2012) Gliding arc plasma-stimulated conversion of pyrogas into synthesis gas. *IEEE Trans Plasma Sci* 40(4):1124–1130
19. Han J, Peethambaran B, Balsamo R, Fridman A, Rabinovich A, Miller V, Fridman G (2015) Non-equilibrium plasmas in agriculture. In: *2015/7 presented on 22nd international symposium on plasma chemistry*, Antwerp, Belgium, pp 17–19
20. Lewis AJ, Joyce T, Hadaya M, Ebrahimi F, Dragiev I, Giardetti N, Yang J, Fridman G, Rabinovich A, Fridman AA, McKenzie ER (2020) Rapid degradation of PFAS in aqueous solutions by reverse vortex flow gliding arc plasma. *J Environ Sci: Water Res Technol* 6(4):1044–1057

21. Fridman A, Kennedy L (2004) *Plasma Phys Eng* 853
22. Stratton GR et al (2017) Plasma-based water treatment: efficient transformation of perfluoroalkyl substances in prepared solutions and contaminated groundwater. *Environ Sci Technol* 51(3):1643–1648
23. Chernets I et al (2011) Development of high-power plasma reformer and power supply for large scale applications. In: 20th international symposium on plasma chemistry
24. Robinson RD et al (2012) Plasma acid production in a gliding arc plasmatron. *Plasma Med* 2(4)

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