Transient Gliding Arc for Fuel Ignition and Combustion Control

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Abstract

Atmospheric and high pressure discharges have been extensively studied during the last three decades for ignition and combustion support. In particular, thermal DC arc and non-thermal corona discharges were utilized. Thermal plasma discharges, like DC arc, are associated with very high gas temperatures (~10,000 K), NOx emissions in case of air and electrode lifetime. Non-thermal plasmas usually cannot provide necessary level of energy density for ignition and combustion support. Thus the challenge is to combine advantages of both thermal and non-thermal discharges by developing powerful and high pressure system, for non-equilibrium plasma generation, which could be efficiently used for reliable ignition, combustion stabilization and at the same time keeping NOx emissions at a minimal level.

To create such powerful non-equilibrium plasma we use transient gliding arc (GA) discharge. This reactor designed in cylindrical geometry produces gliding arc discharge that is a strongly non-equilibrium low current, high voltage arc column, which moves over the electrodes keeping their erosion to minimal with a relatively high power density. The gas temperature in this transient discharge is relatively large (>2000K) but the arc is not in the thermal regime. Vortex flow provides complete thermal insulation of the discharge zone at the same time efficiently cools the arc with intensive convective heat transfer. These properties make it very attractive for above-mentioned application.

Preliminary study involved this transient GA arrangement inside a reverse vortex (tornado) reactor. This arc ignites premixed or non-premixed methane air mixture inside the burner. At high working flow rates we observe a stable gliding arc column with flame in the central zone of the tornado. In fact both flame and gliding arc support each other and cannot exist without the other in similar conditions. Very low current gliding arc column was achieved. Measurement for NOx production in this system is done at different conditions. High power density, very low NOx production, high effectivity and efficiency make the atmospheric pressure transient Gliding Arc discharge promising technology for combustion control.

Introduction

Combustion comprises of three important steps: ignition, flame stabilization and reaction completion [1]. As flow rates increase with power requirements for efficient high power turbines and internal combustion engines there is very short residence time for ignition, flame stabilization and reaction completion. In particular, the case of higher hydrocarbon fuel due to its high density and endothermic decomposition properties results in a longer ignition and combustion time. Therefore, there is a crucial need to dramatically shorten the ignition time and to enhance the combustion and flame stabilization. The faster we achieve ignition and a stable flame, the more time we get for reaction completion and thus minimal emissions and maximum efficiency.

An effective way to enhance ignition and combustion is by the use of electrical discharges (plasma). In particular the equilibrium thermal plasma such as air-fuel plasma has high power and can provide thermally dissociated hydrocarbon and oxygen radicals at high temperature. However, the formed radical lifetime is very short, and the energy addition is confined in a very limited overheated region and is not optimized for gas chemistry and a huge amount of energy is wasted in heating. The cold non-equilibrium plasmas such as glow, corona and dielectric barrier discharges etc. have efficient dissociation and offer good chemical selectivity. However, they are limited by power density and gas temperature is not sufficiently large for ignition. Recent research showed that high current AC, DC and microwave plasma are not useful in producing fuel pyrolysis [2]. Therefore, excellent plasma for combustion enhancement should simultaneously have a large power range and a high degree of non-equilibrium to support selective chemical process. In addition, it must be able to provide long lifetime of various active radicals and hydrocarbon fragments, and to support high flow rate for mixing.

The objective of this study is to achieve transitional plasma i.e. combining advantages of both thermal and non thermal plasma to get chemical process selectivity with high degree of non-equilibrium with gas temperatures high enough to support combustion but at the same time taking care that not a lot of electrical energy is wasted in resistive heating.

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Technical background:

Enhancement of ignition: Ignition at high temperature has two chemical processes. One is the radical initiation time (t_i), and the other is the chain-branching or thermal explosion time (t_b) [1]. The total ignition time is

$$T_{ig} = t_i + t_b,$$
$$t_i \ \alpha \ \exp (E_i / RT) / Ai,$$
$$t_i \ \alpha \ \exp (E_i /RT) / A_b$$

Where E_i and E_b, and A_i and A_b are respectively the activation energy and reaction frequency factors of the key chain initiation and chain branching reactions. *R* and *T* are, respectively, the universal gas constant and gas temperature. For example in the case of hydrogen-air mixtures, the key chain-initiation and chain branching reaction are, respectively,

Initiation:

$$H_2+O_2=H+HO_2 \quad (1)$$
$$(A=7.3E13\ cm^3/mole/s,\ E=58382\ cal/mole)$$

Branching:

$$H+O_2=OH+O \quad (2)$$
$$(A=2.2E14\ cm^3/mole/s,\ E=16507\ cal/mole)$$

There are two ways to reduce the chain-initiation time. One is the thermal addition and the other is the radical addition (chemical enhancement). The thermal addition is to raise the local temperature to accelerate reactions (1) and (2). The radical addition is to add radicals such as H and OH directly to the mixture, so that the time required for chain initiation is removed. Most of the radicals will quickly recombine and return the chemical energy back to thermal energy, but since the radical addition removes the long chain-initiation time, the total ignition delay time can be shortened by one-order or more. But in the case of these reactions temperature increase can reduce the ignition time exponentially. This explains why cold non-thermal plasmas are not as effective in this application as thermal plasmas. But again the purpose is not to provide too much energy in ohmic heating of the fuel-air mixture; rather provide sufficient temperature..

Ignition enhancement using plasma: High-pressure non-thermal gas discharges are considered as cold discharges when the gas temperature does not change significantly or the thermal ionization does not take place, for example, in corona or dielectric barrier discharges. These can effectively provide radicals to the mixture, so that the time required for chain initiation is removed. But these have low electron density; low temperature levels and lower specific power limit their use for combustion applications [3]. On the other hand, gas becomes hot in thermal discharges where thermal effect in ionization is predominant as in thermal arc plasmas or in RF ICP. These discharges have been experimented with a lot for combustion applications but they are inefficient as a lot of energy is wasted in resistive heating and because of no chemical selective chemical process stimulation [4].

There are also discharges with plasma parameters between those of the thermal and non-thermal discharges. Such discharges should be considered as transitional non-thermal discharges, where the gas temperature increases considerably but the discharges still are not in the thermal regime. Gas temperature in the case of transitional discharges is in the range of 2,000-4,000K, which is much less than the electron temperature (>10,000 K) [5]. The ionization of gasses in transitional discharges is defined by direct electron impact or step-wise electron ionization [6]. Direct electron impact involves the interaction of an incident high-energy electron and a neutral atom or molecule. In the step-wise mechanism electron energy for ionization may be significantly lower as molecules are primarily electronically excited. Transitional plasma parameters can be realized in the transient gliding arc discharge.

Gliding Arc: Figure 1 shows a sketch of a conventional gliding arc system, generating non-stationary discharge [7]. The arc starts in a narrow gap at the low end (marked i in Fig. 1) between two diverging flat electrodes in a gas flow. It starts immediately after breakdown, a process that takes place when the electric field in the gap is high enough to ignite the arc. The current of the arc increases very fast and accordingly the voltage on the arc drops rapidly. If the gas velocity is strong enough to push the arc downstream, it forces the arc to move along the diverging electrodes (i.e., to glide) and elongate. The elongated arc demands more power to sustain itself. It continues to elongate until the power supply can no longer compensate the energy lost through

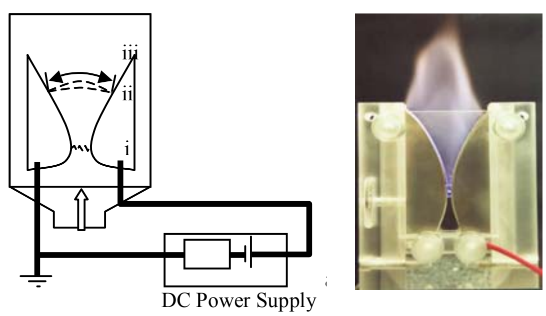


Fig. 1: Conventional Gliding Arc. (a) - Schematic of gliding arc: (i) Point of gliding arc ignition, (ii) Point of developed gliding arc when Maximum Energy is transferred, (iii) Point of total extinction. (b) Picture of flat gliding arc discharge.

heat transfer to the surrounding gas. At this point the arc cools down and finally extinguishes. Immediately after the extinction, the next cycle starts as soon as the potential difference reaches the breakdown value, an event which is usually just after the fading of the previous arc.

The gliding arc (GA) can exist in two different regimes: the high-current GA (HCGA, with current, $J \geq 10$ A) and the low-current GA (LCGA, $J \leq 1$ A). The former starts as an equilibrium discharge and is associated with thermal ionization effects, whereas the latter is a non-equilibrium transitional discharge during the whole cycle of the evolution. As a simplification HCGA can be considered as a conventional thermal arc with a strong convective cooling by a fast transversal gas flow and with specific boundary conditions on the electrodes. On the other hand, LCGA can be considered as a high voltage atmospheric-pressure discharge (HVAPD) [7], also with a strong convective cooling by fast transversal gas flow, and with specific boundary conditions on the electrodes [7].

In general, if intensive cooling of any electrical discharge is compensated by the increase in the electric field strength, the role of non-equilibrium mechanisms of ionization increases [6]. Thus, in order to get more non-equilibrium conditions in the arc discharge, it is necessary to increase the cooling of the discharge without increase in the current strength. This is the reason why the GA with intensive convective cooling is more non-equilibrium than HVAPD for the same current. The LCGA is thus a good example of a transitional discharge, providing benefits of both thermal and non-thermal discharges: high plasma density, high power and high operating pressure (typical for thermal plasma systems) and a high level of non-equilibrium, high electron temperature, intermediate gas temperature, resulting in the possibility of stimulating selective chemical processes without the need for quenching (typical for non-thermal plasma systems). These properties of transitional GA discharges make it attractive for many industrial applications.

Reverse Vortex Flow (RVF) or "Tornado": The present work utilized a reverse vortex flow (RVF) in a cylindrical volume, the flow that is similar to the natural tornado. To obtain the RVF, pressurized gas entered the cylindrical volume tangentially and the gas flow exited from the top of the cylindrical volume, i.e., the same side as the gas entry was placed (see Fig. 2). The diameter of the exit was considerably smaller than that of the cylindrical vessel. Figure 2 shows the flow direction of gas in the reverse vortex flow (RVF) used in the present study: (i) three-dimensional sketch of flow and (ii) sketch of streamlines on the axial plane.

The RVF had been used in atmospheric-pressure electrical discharges such as microwave (MW) discharge, and radio frequency inductively coupled plasma (RF ICP) [8]. The tornado geometry was also applied to gaseous flame, which could be also considered as low-temperature plasma. In the cases of MW discharge and RF ICP plasma generators and gas combustion chamber, the RVF was compared experimentally (through calorimetric investigations) and numerically with conventional "forward" vortex flow (FVF) [9]. The thermal efficiency of a reverse vortex was found to be much better than that of the forward vortex flow system.

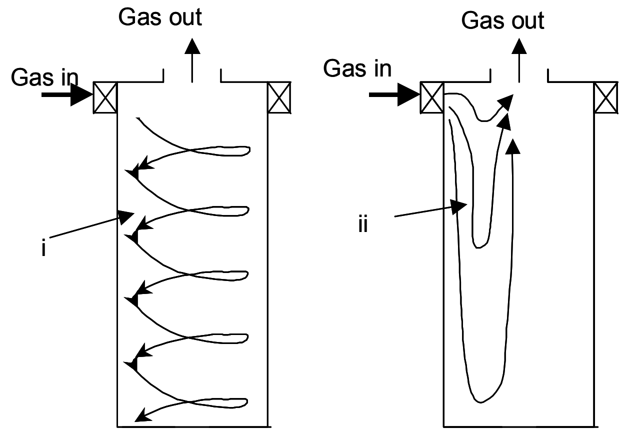


Fig. 2 Reverse vortex ("tornado") flow in a cylindrical reactor. (i) - Three dimensional sketch of flow. (ii) - Stream lines sketch on axial plane.

The tornado flow obtained in the RVF ensures high gas velocities necessary for the gliding arc and very effective heat and mass exchange at the central zone of the plasma inside the cylindrical volume because of the fast radial migration of the turbulent micro-volumes and deceleration near the tube walls [5]. Thus, development of the Gliding Arc in Tornado (GAT) makes most use of the properties of the RVF for enhancing non-equilibrium LCGA plasma parameters.

Plasmatron Design:

Figure 3 shows the present plasma reactor system used to produce a gliding arc in reverse vortex flow inside a quartz tube indicated by (1) in Fig. 3. The tube enclosed a cylindrical volume (2). At one end of the tube a swirl generator (3), with tangential inlet holes to the cylindrical volume (2), injected air or fuel-air mixture. Gas outlet (5)

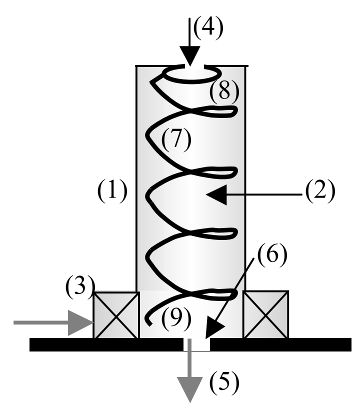


Figure 3. Plasmatron Design

in the plasma reactor was on the same side as the swirl generator, setting up reverse vortex. An axial inlet (4) was at the bottom end of the cylindrical reactor so that one had the flexibility to introduce additional air or any other reacting gas as desired. The circular edge (6) of the outlet (5) acts as the ground electrode for discharge. An inconel spiral (7) is arranged co-axially inside the reactor very close to the walls. The angle of this spiral is made such that it is parallel to the streamlines of the flow avoiding any disturbance to the flow setup. At the end, near the axial inlet (4), this spiral shapes to form a ring (8) smaller in diameter than the spiral (7). The discharge in the gas starts at the point (9) when the electric field across the electrodes is high enough. This initial discharge elongates as the swirling flow drives the arc on the spiral electrode as illustrated in fig. 4. The elongating arc finally reaches the ring (8); since the diameter of the ring is smaller the arc now stabilizes in this low-pressure central region and forms a cylindrical column. The arc moves very fast on the electrodes the contact time is very short so we don't see any deterioration or erosion from the electrode surface. Once the arc is stabilized in the central region its length does not vary much and we have stable low current regime. Even though, the arc is still elongating on these electrodes, which are in effect parallel inside the flow. This elongation is essentially due to difference in velocity of the gas near the electrodes.

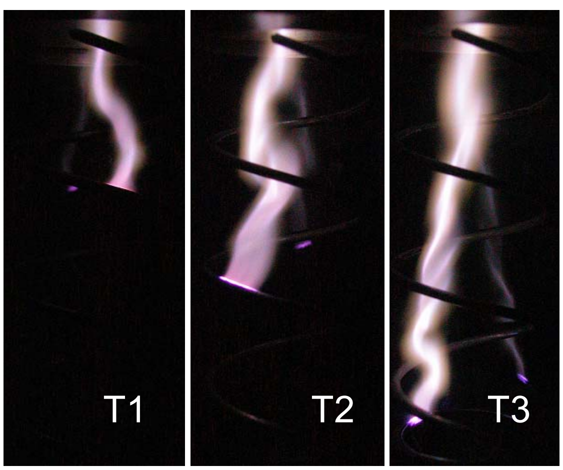


Fig 4: GAT pictures with shot exposition time (1/1000 s), at time T1, T2 and T3, illustrating elongation.

Experimental System and Future Work:

Experimentation to test working of this plasma generator for combustion support and ignition is planned in a vortex burner (similar to turbine engines). The flow to combustion chamber is controlled and different conditions as to mass fuel ratio, velocity, residence time, etc. can be achieved. Plasmatron is connected to this chamber. Jet of high temperature active species from the plasma is injected into the combustion chamber to ignite and then support combustion. The outlet from the combustion chamber is analyzed using analytical equipment like GC/MS (gas chromatograph, mass spec), quantitative H2, CO and CO2 analyzers. Plasma power, voltage on the arc and current is also measured.

Results:

The purpose of using plasma for combustion support is to provide active species. So working medium for plasma can be air, fuel, or a combination of both. In this present study, mostly rich air-fuel mixtures are used and methane is used as the gaseous fuel. In the preliminary tests, initially only with the Plasmatron, different combinations of flow were experimented with to get: (1) maximum power input per unit volume to have effective excitation, (2) non equilibrium plasma conditions so that energy is not wasted in joule heating but maximum amount of active species is produced, and (3) minimum NOx emissions from Plasmatron.

Following important observations were made in these experiments:

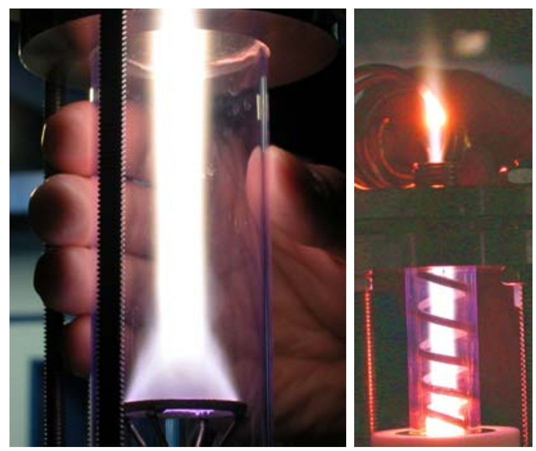


Fig. 5. A. and B. GAT reactors in operation

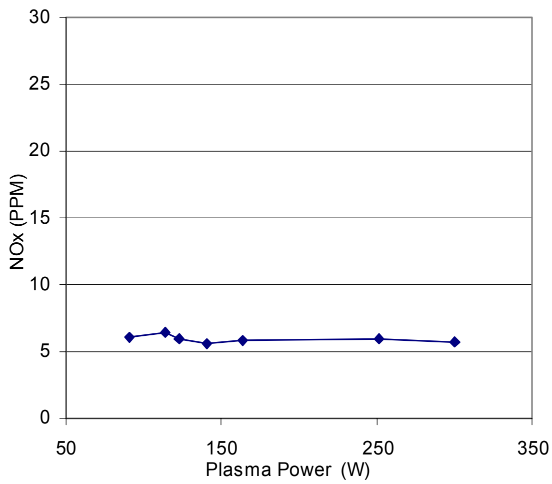
a) Fig. 5 shows stable Plasma column in central region of the reverse vortex flow. The outlet jet form the Plasmatron was at high temperature (>1000 K). But the reactor walls and electrodes remained relatively cold. Wall temperature was measured at 60 degree C. All the energy input to the Plasmatron thus remains in the gas jet, which then enters the combustion chamber. Figure 5 B shows GAT reactor (diameter = 9mm and length = 20mm) with transient GA plasma in rich fuel air mixture.

b) When arc is in the fuel-air mixture rather than in pure air we get about 6 times lower NOx with other conditions

Methane (L/min.)	Methane (L/min.)	AIR (L/min.)	Equivalence ratio	NOx (PPM)	Power (W)
Axial	Tangential	Tangential			
5.7	0	43	1.27	37	90
0	5.7	43	1.27	6.1	90

reaming the same. This is achieved when fuel is injected from swirl generator side of the Plasmatron.

c) When electric power input (plasma energy) was increased we did not have any increase in NOx production inside the palsmatron. The flow conditions for these experiments were kept the same through out so that we have same equivalence ratio and flow velocities but electric (plasma) power input increases. Higher specific electric power addition does not affect NOx emissions.



d) For similar flow conditions GAT with higher voltage had lower NOx formation. When voltage on the arc increases, it enables the DC arc to grow more in length, the longer arc has more surface area and losses more and more energy as it grows. This rapid cooling of the arc makes plasma more non-equilibrium and reduces NOx formation, which is dominated by thermal mechanism.

Methane (L/min.)	AIR (L/min.)	Voltage (KV)	Current (mA)	NOx (PPM)	Power (W)
Axial	Tangential				
6.2	43	4.4	29	50	63.8
7.5	43	5	29	40	72.5
4.7	43	5.2	28	36	72.8

Discussion

Advantages of GAT are almost-perfect thermal insulation and intense convective cooling of the discharge zone. The electric field in GAT transitional plasmas is relatively strong, and both translational and electron temperatures are strongly coupled. The present GAT works in regimes where the extinction and reignition do not take place regularly; these regimes can be described as more or less constant, strictly as non-equilibrium, transitional or thermal, depending, first of all, on the current and the intensity of the flow. According to the electric circuit arrangement of the 2-D flat gliding arc shown in Figure 1, the maximum current in the arc (J_{max}) and the current at maximum power dissipation (J_W) become as follows:

$$J_{max} = V/R \text{ and}$$

$$J_W = V/2R$$

According to the thermal GA theory [6], J_W has a minimal current at the maximum power dissipation, which is the current just before extinction of the arc. Current below this value of J_W is possible only for a non-equilibrium gliding arc. Electric circuit arrangement for the present GAT was essentially the same as the one shown in Figure 1, power supply having DC output voltage V, current J and internal resistance R. Figure 6 gives a plot from an oscilloscope recording of current signal over time for the present gliding arc. In this experiment, the voltage applied on the system was 10 KV and the resistance was 28.5 KΩ. Thus, according to Ohms law and thermal arc theory, the maximum current and J_w in the present GAT become respectively,

$$J_{max} = 350 \text{ mA and}$$

$$J_W = 175 \text{ mA.}$$

In the present GAT experiments we observed that the current remained relatively constant and the value of current varied in a range of 150–250 mA. Note that we did not observe the current that corresponded to the maximum current during the present GAT cycle, the

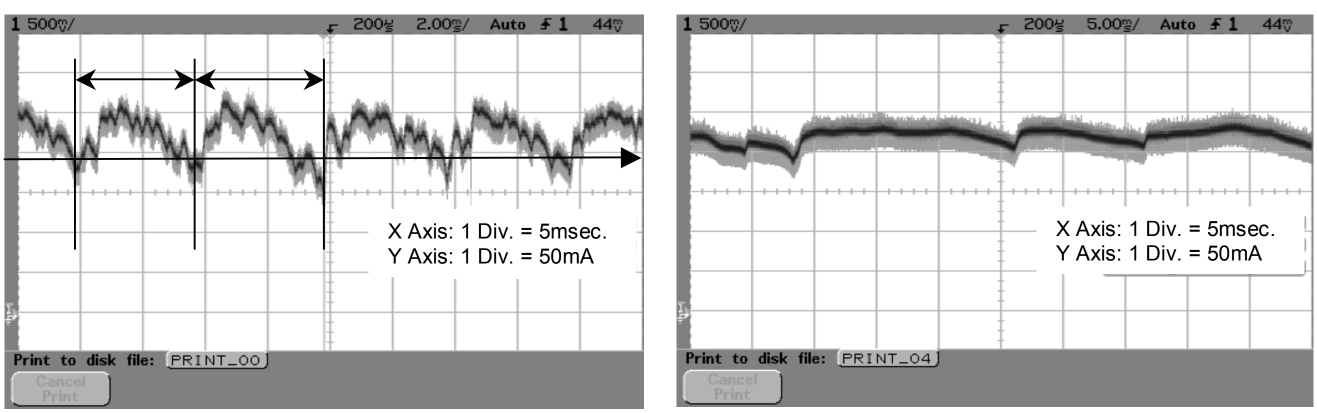


Fig. 6 Current-Time Characteristics- A. On spiral Electrode (frequency 100Hz) and B. On ring electrode.

value which should have been obtained at a short distance ignition regime if we had the extinction and reignition periodically. The lowest current observed (150 mA, see Fig. 6) in the present GA experiment was less than J_w = 175 mA. Thus, we conclude that the GAT is in the "overshooting" regime, which was also observed in the case of 2-D flat low-current gliding arc [7]. The average current J_{AVG} was about 200 mA, which was close to the current J_w corresponding to the maximum power dissipation on the arc. As we further increase the distance between the electrodes we got a much flatter curve as shown in Fig. 6B because at these large separation of electrodes the shortest arc was already relatively long with no further possibility of sizeable elongation. Thus the gliding arc could be stabilized in strictly non-equilibrium transitional regimes.

The period of a GAT shown in Fig. 6A was about 10 ms (not very regular because there is no special place for arc extinction) and its corresponding frequency was 250 Hz. The frequency of the present GAT cycle involving the elongation, extinction and reignition varied according to the gas rate. As the flow rate of air varied from 0.5 L/s to 2.5 L/s, the gliding arc frequency varied from 100 Hz to 500 Hz in the present study.

Conclusion:

The present gliding arc in tornado (GAT) existed in a manner that the non-equilibrium transitional gliding arc was extremely elongated between two electrodes with a constant distance. We observed an overshooting regime of the arc with the current value less than the minimum current predicted by the theory of thermal arc [7]. The "overshooting" regime observed in the present atmospheric pressure GAT confirmed that the discharge was in non-equilibrium conditions. In contrast to conventional thermal and non-thermal discharges, the transitional GAT discharges are able to provide advantages of both thermal and non-thermal discharges. The benefits of the present GAT, such as a high level of non-equilibrium and a large power density, high electron temperature, etc. make the GAT very attractive for fuel ignition and combustion support applications. The experimental results showed low NOx emissions, which can be further reduced by proper selection of flow regimes keeping same air-fuel ratio. Further study on the subject is being carried out and better understanding of the process can be established from gas chromatography results that are yet to be done. Another interesting issue is what is the affect of using different kinds of fuels/gasses for plasma generation. Effectiveness of RVF to enhance the properties of transitional plasma and thermal insulation as reported earlier has been verified.

References:

1. Ju, Y.; "Supersonic Combustion: Theory and experiment", Combustion research, Vol.105, 1-16, 1996.
2. Yao, S. L., Suzuki, E., Nakayama, A., "The pyrolysis property of a pulsed plasma of methane", Plasma Chemistry and Plasma Processing 21:651-663, 2001.
3. Sobacchi M.G., Saveliev A.V, Fridman A.A, Kennedy L.A, Ahmed S, Krause T. 2002, International Journal of Hydrogen Energy 27, Pg. 635-642.
4. Marie, Iulian Rusu, 2001 J. Phys. D: Applied Phys. 34, Pg. 2798-2803.
5. C. S. Kalra, M. Kossitsyn, K. Iskenderova, A. Chirokov, Y. I. Cho, A. Gutsol, A. Fridman, "Electrical discharges in the Reverse Vortex Flow – Tornado Discharges". – Electronic Proceedings of 16th International Symposium on Plasma Chemistry, Taormina, Italy, June 22-27, 2003. ISPC-565.pdf.
6. A. A. Fridman, L. Kennedy "Plasma Physics and Engineering" (Taylor & Francis, accepted for publication in 2004).
7. Fridman, A., Nester, S., Kennedy, L.A., Saveliev, A. and Yardimci, O.M., "Gliding arc gas discharge", Prog. Energ Combust. Sci. 25:211-231, 1999.
8. Gutsol A. Thermal Insulation of Plasma and Flame in Reverse Vortex. In: Progress in Plasma Processing of Materials 1999. Editors: Pierre Fauchais and Jacques Amouroux. Begell House, Inc., NY, 1999. (Proceedings of the Fifth International Thermal Plasma Processes Conference, St.-Petersburg, July 13-16, 1998) P. 81 - 86.
9. Gutsol A. F. and Kalinnikov V. T. Reverse-Flow Swirl Heat Insulation of Plasma and Gas Flame. - High Temperature, Vol. 37, No. 2, 1999, pp. 172 - 179.