White Paper for *Frontiers of Plasma Science Panel*

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	"P", "S"
• Plasma Atomic physics and the interface with chemistry and biology	S
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• Plasma self-organization	P
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Oral	
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Title:	Specific Localization of High-Voltage Discharge at Interface of Two Gases
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(Limit text to 3-pages including this form. Font Times Roman size 11.
1 page of references and 1 page of figures may also be included. *Submit in PDF format*.)

- ***Describe the research frontier* and importance of the scientific challenge.**

The effect of the electric discharge specific localization appears at the breakdown and development of a long filamentary high-voltage discharge generated in a non-homogeneous gas media such as a shear layer between two flows of different gases, gaseous jets, or at an inter-gas interface of any other origin. It was found experimentally that the discharge closely follows a boundary between two gases in most of those cases, see [1-3] and references therein. Later [4], a similar behavior of a quasi-DC discharge has been described at the air-fuel-plasma interaction in a supersonic airflow. The fact that discharges can be well-guiding by solid [5], liquid [6] interfaces and by gaseous jets [7] is widely known and well understood. Contrary to those the mechanism of discharge localization at the interface of two molecular gases is not yet explained properly. Extra experimental and theoretical efforts should be performed to open a pathway for practical applications of the phenomenon.

One of the major practical results of a fundamental study of filamentary atmospheric plasma specific localization could be in a wider use of plasma technology for combustion enhancement through mixing intensification and ignition of air-fuel with a non-premixed composition at non-optimal conditions. Long filamentary discharges of submicrosecond duration were considered as a feasible source of fast gas perturbations [10]. They appear mostly in two phenomena: (1) instability of a rapidly expanded boundary between the heated/pressured zone and ambient atmosphere; and (2) gaseous jets generation due to the cumulating of shock waves, induced by electrical discharge [8-10]. The prediction and control of

atmospheric lightning is one more example of a potential technical breakthrough gained due to a study of the phenomenon.

- ***Describe the approach to advancing the frontier and indicate if new research tools or capabilities are required.***

A laboratory-scale test demonstrating the effect of specific localization has been performed in air, N2, C2H4, and CO2 and their non-premixed compositions. The triggered pulse discharge is generated by means of the specially designed power supply based on a Tesla coil with impulse excitation. An important feature of the power supply is the rapid voltage rise, $dU/dt > 2\times10^{11}$ V/s. Tests were performed in ambient conditions and in a high-speed flow at the following parameters: air pressure P = 1 Bar at M=0 and P = 0.2-0.8 Bar at M=2-0.3; inter-electrode gap d=30-80 mm; discharge main pulse duration τ = 30-80 ns; maximum voltage U_{max} = 80-120 kV; maximum current I_{max} = 1-3 kA; maximum power release W_{max} = 20-110 MW; and energy deposition in single-pulse mode E_d = 1.0-2.7 J. Instrumentation includes voltage and current probes, OES, a schlieren system, and fast triggered cameras.

The discharge duration is rather short compared to the gasdynamic processes occurring after the pulse. The gas movement after the high energy density deposition appears to be unstable and goes through several stages. On the first stage (t<50 μs) the channel looks quite classical: a cylindrical thermal cavity and a shock wave running away. Note, even in the early stage small-scale instabilities of the discharge channel were observed. A working hypothesis of the origin of these perturbations is the electromagnetic nature due to the interaction of the high electric current with its own azimuthal magnetic field. At t=80-150 μs the shape of the after-spark channel is intensely unstable. The physical mechanism of this instability was considered in [9, 11]: cooling of the axial zone leads to a pressure decrease with a sequential reversal of gas movement. Such a movement occurs unstable due to the Rayleigh-Taylor mechanism.

The effect of specific localization has been demonstrated experimentally for all pairs of gases mentioned above. The explanation of this fact includes the idea that the discharge localization is managed by the rule of minimal electric field, required for the discharge maintenance, along the line of breakdown. The discharge "prefers" the path in the gas1, gas2, or between them depending on conditions and the phase of the discharge development. For a short-pulse discharge, the first stage of the spark breakdown is the propagation of multiple streamers from the "hot" electrode toward the grounded one. In the case of a high-power electrical source, the streamers occupy a significant volume of gas, covering all possible paths for further development. This statement is illustrated by the schlieren photo of the phase of the streamers in Fig. 1a. The next phase consists of the selection of the discharge pathway among multiple channels with nonzero conductivity. This is the key point – the channel appears to be the best in terms of the current increase, i.e. possessing higher conductivity and lower inductivity. If the surrounding media is nonhomogeneous, the favorite path may not be the shortest one. Tests demonstrate that the best conditions for discharge development may be realized in the air-fuel mixture but not in air or fuel, as it is shown in schlieren image of the discharge breakdown at the presence of two gases in Fig. 1b.

In order to estimate a possible mechanism of such effects, the computational analysis of plasma properties in fuel/air (C_2H_4/air in this particular case) mixtures of various compositions was performed [12]. The most important quantity governing discharge breakdown is the rate of electron multiplication equal to the difference between electron impact ionization and attachment rates. Figure 2a shows the difference between the total ionization and attachment rates as a function of relative ethylene concentration at various E/N parameter values. Ionization and attachment rates were calculated by numerically solving the electron Boltzmann equation for steady state conditions with a two-term approximation for the electron velocity distribution function. The necessary electron scattering cross sections for N_2, O_2, and C_2H_4 molecules were taken from refs. [13-15]. It is seen that at E/N =100 and 150 Td (1 Td=10^{-17} V·cm^2) the multiplication rate as a function of ethylene concentration has a maximum value around 0.5. It means that in the course of mixing two jets the discharge would most likely be located within a region with nearly equal concentrations of ethylene and air. Under experimental conditions the discharge evolves to a high current form. The dynamics of transition from low-current to high-current form was simulated in [12] to explore the most beneficial trajectory for the breakdown. The model formulated in [13] was used, which is applicable for

uniform non-thermal plasma in air, and added the processes associated with the appearance of the new component C_2H_4. Figure 2b shows a time evolution of the electric current for various gas compositions. The discharge breakdown time, defined as a moment of current approaching 2 A, is ordered for mixtures under consideration as follows: 1.77 μs for C_2H_4:air =1:1; 1.95 μs for pure C_2H_4; 2.02 μs for C_2H_4:air= 6.25:93.75 (ER=1); and 2.59 μs for dry air. Thus the model predicts the lowest breakdown voltage (94 kV) for the mixture C_2H_4:air =1:1. At earlier stages of evolution the discharge current density grows more rapidly in pure ethylene. This means that the plasma filament in a course of development may wander in space searching for the best local conditions for the breakdown. In some situations (pairs of gases) this consideration is not enough to explain the phenomena.

Special tests were arranged to prove the effect of discharge specific localization in high-speed two-component flow. The experimental approach includes the following key points: supersonic duct-driven airflow M=0.3 and M=2.5; direct wall injection of gaseous fuel or model gas; and transversal short-pulse repetitive electrical discharge, crossing the air-fuel-air zone. The experimental scheme is shown in Fig.3a. The jet of secondary gas was injected from the wall through an orifice D=4mm with sonic velocity. The grounded electrode was combined with the nozzle. The "hot" high-voltage electrode was installed on the opposite wall of the duct a bit downstream with respect to the grounded one. Injected gases were C2H4 (fuel), CO_2 (model of fuel and product), and He (model of hydrogen). Schlieren photos in Fig.3b-d demonstrate a CO_2 jet in flow, a discharge operation without a CO_2 jet, and the discharge with the jet under conditions of subsonic flow (the result in supersonic flow was qualitatively the same). It is clearly seen, that discharge breakdown occurs along the jet.

Extra efforts should be performed for a detailed study of the effect of specific localization, including both experimental and theoretical research. The complexity of the problem is in the combination of kinetic, electrodynamic, and hydrodynamic processes appearing at a short time scale. The advanced gasdynamic and electrical high-voltage experimental equipment is available at the University of Notre Dame along with basic diagnostic apparatuses. The application of an advanced measuring technique (local non-intrusive measurements of electric field strength and electric conductivity of gas) and a novel predictive tool is of urgent necessity. For example, at high gas pressure the CARS technique [16] could make possible two-components electric field measurements using a single laser shot, such that there would be no need in repetitive pulsing.

- ***Describe the impact of this research on plasma science and related disciplines and any potential for societal benefit***.

This research is one example where a variety of physical processes working at the same time delivers an extra complexity of the problem and requires advanced measuring and predictive tools to be applied. The plasma-based kinematic and, probably, molecular mixing intensification opens a novel field for plasma implementation. A significant impact may be expected on experimental methods for plasma research and have a long term effect on further applications of plasma science/technique in the fields of aerospace engineering, fluid mechanics, and chemical engineering.

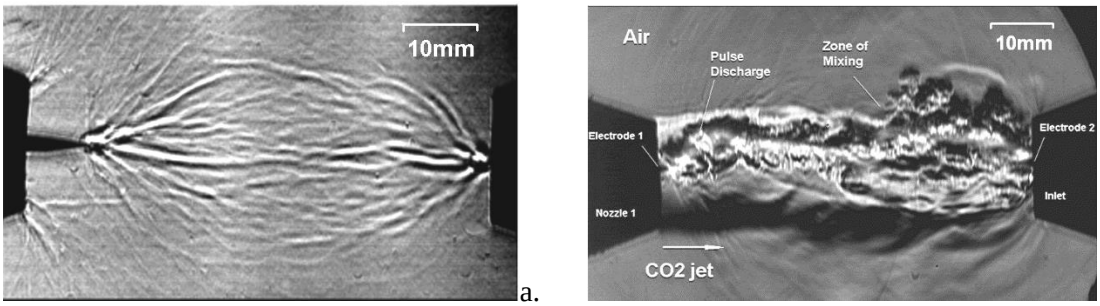
Main directions in the advancement of the design of an internal combustion apparatus are related to effectiveness, economic issues, and environmental conservation. However, there are technical difficulties in ignition and combustion maintenance especially at high flow speeds and low temperatures of the reactive components. Utilization of the transient nonequilibrium electrical discharge is the state-of-the-art direction both in a fundamental study and for technical issues. Mixing, ignition, and stabilization of combustion in supersonic flows are the problems of major fundamental and applied importance in the development of high-speed vehicles. Utilization of plasma generated by electrical discharges is the modern promising approach for improving the combustion process in high-speed engines.

The knowledge or better prediction of the atmospheric electric discharges localization may lead to significant modification of current state-of-the-art techniques in lightning protection and in the safety of high-voltage transmitting lines.

References (Maximum 1 page)

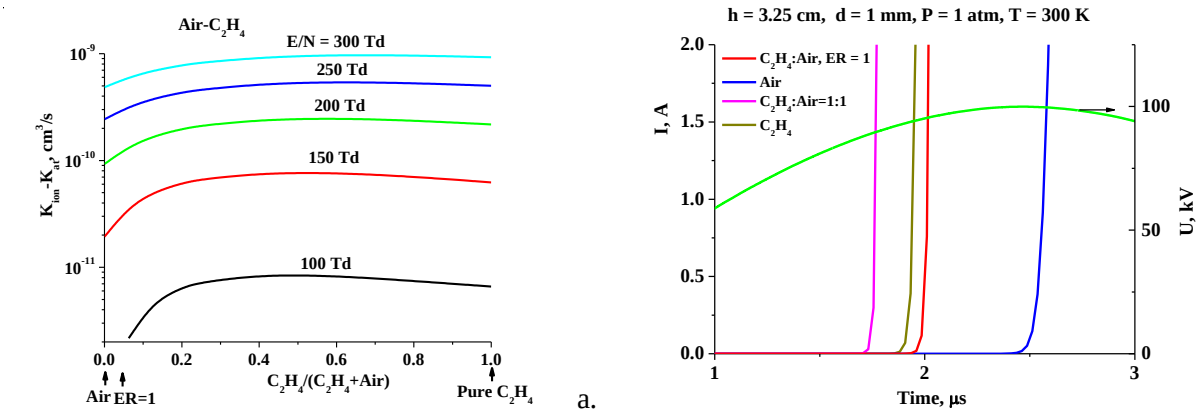
1. S. B. Leonov, A. A. Firsov, Y. I. Isaenkov, M. A. Shurupov, D. A. Yarantsev, "Plasma-Based Fast Mixing and Ignition in Supersonic Flow", Paper AIAA 2011-2327
2. S. B. Leonov, D. A. Yarantsev, "Instability in Post-Discharge Thermal Cavity," IEEE Transactions, Plasma Science, Vol. 36, No. 4, 2008, p. 978.
3. S. B. Leonov, Yu. I. Isaenkov, D. A. Yarantsev, I. V. Kochetov, A. P. Napartovich, M. N. Shneider "Unstable Pulse Discharge in Mixing Layer of Gaseous Reactants", Paper AIAA-2009-0820
4. Konstantin V. Savelkin, Dmitry A. Yarantsev, Igor V. Adamovich, and Sergey B. Leonov, "Ignition and flameholding in a supersonic combustor by an electrical discharge combined with a fuel injector", Combustion and Flame, Volume 162, Issue 3, March 2015, Pages 825-835
5. Z. Xiong, E. Robert, V. Sarron, J-M. Pouvesle and M. Kushner, "Dynamics of ionization wave splitting and merging of atmospheric-pressure plasmas in branched dielectric tubes and channels", 2012 J. Phys. D: Appl. Phys. 45 275201
6. V. Petrishchev, S. Leonov, and I. Adamovich, "Studies of Nanosecond Pulse Surface Ionization Wave Discharges over Solid and Liquid Dielectric Surfaces", Plasma Sources Science & Technology, 2014, vol. 23, 2014, p. 065022
7. Mounir Laroussi and Tamer Akan, "Arc-Free Atmospheric Pressure Cold Plasma Jets: A Review", Plasma Processes and Polymers, Volume 4, Issue 9, pages 777–788, November 22, 2007
8. Greig, J. P., Pechacek, R. E., Raleigh, M., "Channel cooling by turbulent convective mixing," Phys. Fluids, Vol. 28, No. 8, 1985, pp. 2357–2364.
9. Shneider, M. N., "Turbulent decay of after-spark channels", Phys. Plasmas, Vol. 13, 073501 (2006)
10. A. Firsov, S. Leonov, et al "Mixing Actuation by Unstable Filamentary Discharge", Paper AIAA-2013-1188
11. S. B. Leonov, Y. I. Isaenkov, A. A. Firsov, S. L. Nothnagel, S. F. Gimelshein, and M. N. Shneider, "Jet Regime of the Afterspark Channel Decay", Physics of Plasmas 17, 1, 053505, 2010.
12. M.A. Shurupov, A. A. Firsov, Yu. I. Isaenkov, S. B. Leonov, D. A. Yarantsev, M.N. Shneider, I.V. Kochetov, A.P. Napartovich, "Gasdynamic Effects of High-Voltage Breakdown in Non-Homogeneous Atmosphere", Proceedings of 11th International Conference on Fluid Control, Measurements and Visualization: FLUCOME 2011 – Paper No. 064; December 5-9, 2011, Taiwan
13. Akishev Y.S., Deryugin A.A., Karalnik V.B., et. al., (1994) Numerical simulation and experimental study of an atmospheric-pressure direct-current glow discharge, *Plasma Phys. Rep.*, 1994, 20, 511-524.
14. Ionin A.A., Kochetov I.V., Napartovich A.P., Yuryshev N.N., (2007) Physics and engineering of singlet delta oxygen production in low-temperature plasma, *J. Phys. D: Appl. Phys.*, 2007, 40, R25-R61.
15. Hayashi M., (1990) Electron collision cross sections determined from beam and swarm data by Boltzmann analysis in "Nonequilibrium Processes in Partially Ionized Gases" Eds. M. Capitelli and J. N. Bardsley, *NATO ASI Series B: Physics* v. 1990, 220, 333-340, Plenum Press, N-Y
16. B.M. Goldberg, I. Shkurenkov, S. O'Byrne, I.V. Adamovich, and W.R. Lempert, "Electric Field Measurements in a Dielectric Barrier Nanosecond Pulse Discharge with Sub-Nanosecond Time Resolution", Plasma Sources Science and Technology, 24 (2015) 035010

Figures (maximum 1 page)



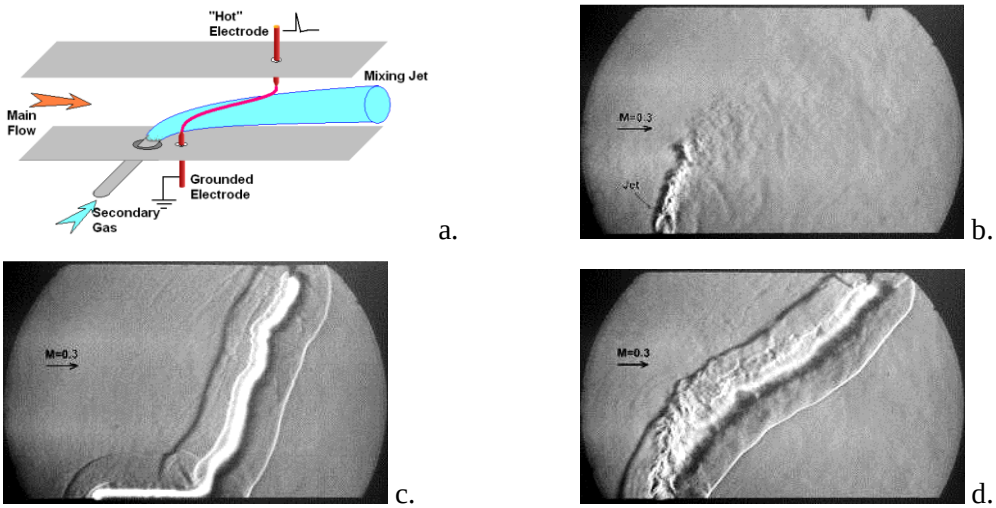
a. b.

Figure 1. Schlieren images of the discharge development. a - streamer phase; delay time is 0.5ms after the shot. b – the discharge interaction with CO2 jet in air; image is captured in 0.2ms after the shot.



a. b.

Figure 2. Result of the simulation of discharge development in fuel/air mixtures. a - electron multiplication rate as a function of gas composition for various values of the reduced electric field strength E/N, ER=1 is a stoichiometric mixture (6.25% of C_2H_4). b - electric current evolution in a plasma filament of 1 mm diameter in a discharge with cathode-anode spacing d=3.25 cm for various gas compositions, voltage waveform U=100[kV]·sin($\pi t[\mu s]/5$).



a. b. c. d.

Figure 3. Experiment on filamentary discharge localization in high-speed flow. a - experimental scheme. b-d – schlieren images: b – CO2 jet in M=0.3 flow; c – discharge in flow; d – discharge with CO2 jet in flow.