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Plasma-Assisted Combustion for the Energy Transition

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Plasmas are ionized gases produced by applying an electromagnetic field to a gas. The field accelerates the electrons, which then impart their energy to the gas via collisions. These collisions excite, dissociate, and ionize the particles present in the gas, thus creating a mixture of ions, electrons, dissociated molecules, as well as excited atoms and molecules. These energetic particles make the plasma a highly reactive mixture that can promote chemical reactions even at low temperature.

This special feature has made plasmas the solution of choice for many industrial applications, such as the ignition of combustible mixtures. A well-known example is the spark plug, used for over a century to ignite flames in gasoline engines. The spark is a short-lived plasma, lasting a few milliseconds, produced by applying a high electric field of several kilovolts between two electrodes separated by about 1 mm. The spark dissociates and ionizes the fuel-air mixture, producing radical species (such as oxygen atoms) that can effectively initiate combustion reactions. In traditional sparks, the plasma reaches very high temperatures (about 40,000 K) and nearly full ionization in the gap between the electrodes. Spark plugs are also used to ignite jet engines, power generation turbines, domestic heaters, industrial furnaces, and scramjet engines.

Today, more than 80% of the primary energy production is based on the combustion of fossil fuels, responsible for most CO_2 emissions originating from human activity [1]. To curb CO_2 emissions, switching to CO_2-free or CO_2-neutral combustion is crucial. Combustion can be made CO_2-free by burning carbon-free fuels such as hydrogen (H_2) or ammonia (NH_3). CO_2-neutral combustion can be achieved by burning Sustainable Fuels made from waste, sustainable crops, or from CO_2 and renewable electricity.

There is, however, a major issue with these decarbonated flames: they still produce pollutants, in particular NOx, which create severe environmental and health problems because they contribute to acid rain and suffocating smog. The NOx emissions of H_2-air flames are actually even higher than those of traditional fuels because they burn at higher temperatures than traditional hydrocarbons, and because the production of NOx increases exponentially with the flame temperature. The strategy to reduce NOx emissions is therefore to decrease the temperature of the flames. This can be achieved by operating combustors with lean flames, i.e. flames with a lower fuel/air ratio than in traditional, stoichiometric flames (balance between reactants and reaction products). However, lean flames are prone to instabilities and extinction. In extreme cases, instabilities can cause pressure fluctuations that can damage or even destroy the combustion chamber.

This is where plasmas can help. The chemical species produced by electron-impact reactions enhance the reactivity of lean flames and make them easier to ignite or to burn in a stable way. The amplitude of the applied electric field determines the nature and quantity of active species produced by the electron-impact reactions [2]. Many successful demonstrations of lean flame ignition and stabilization by plasma discharges have been made in laboratory-scale combustors over the past decades and are summarized in recent reviews [3,4]. These experiments were conducted with a wide variety of electric discharges including microwave, radio-frequency, and nanosecond discharges. An example of flame ignition by nanosecond discharges is shown in Figure 1 [5].

Flame stabilization is particularly challenging because the discharge must be applied continuously to prevent the flame from becoming unstable or from extinguishing. For this application, it is essential that the electric power needed to sustain the plasma be much lower than the power generated by combustion. An energy efficient way to stabilize combustion is to use Nanosecond Repetitively Pulsed (NRP) discharges.

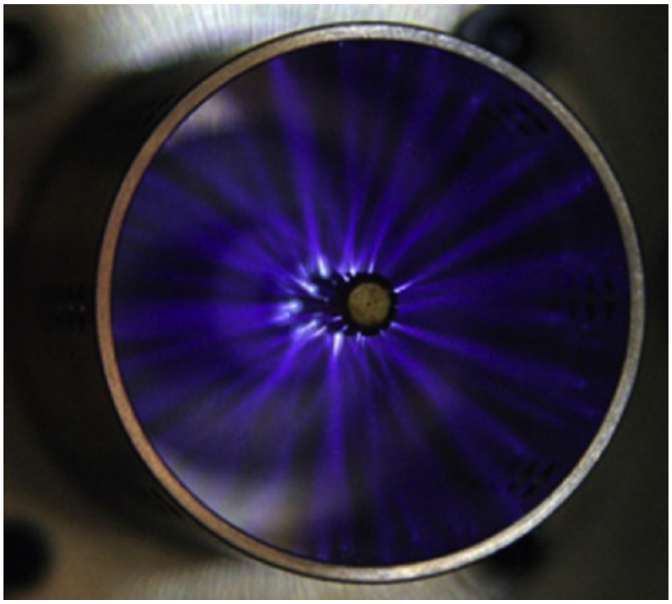

Figure 1. Ignition of a lean C_2H_4/air mixture by nanosecond pulses [5]

Introduced in the early 2000s [6], NRP discharges consist in applying repetitive high voltage pulses (several kilovolts) of short duration (about 10 nanosecond, i.e. ten billionth of a second). Each pulse produces active species that enhance combustion. When these species are consumed, the next pulse produces a new batch of active species. The interval between two pulses must be long enough to minimize the plasma power consumption, but short enough to ensure that enough active species are produced on average. Typical NRP frequencies are in the range of 10-100 kHz, i.e. 100 to 10 microseconds between each pulse.

An example of stabilization of a lean propane air flame by NPR discharges is shown in Figure 2. More generally, NRP discharges can effectively stabilize lean flames for a wide variety of gaseous and liquid fuels (methane, natural gas, propane, kerosene, L-heptane, L-dodecane), for flame powers up to 50 kW and pressures up to 5 bars [7]. In all cases, the NRP plasma power is low, less than 1% of the flame power. Numerical simulations capable of reproducing plasma-assisted combustion effects in lean, premixed, turbulent flames are also becoming available [8, 9].

Several challenges remain to be addressed. First, plasma discharges produce not only active species, but sometimes also NOx, a pollutant which must be minimized to not offset the advantages of plasma- assisted combustion (PAC). Current efforts are focused on better understanding the PAC mechanisms for a variety of fuels and on developing

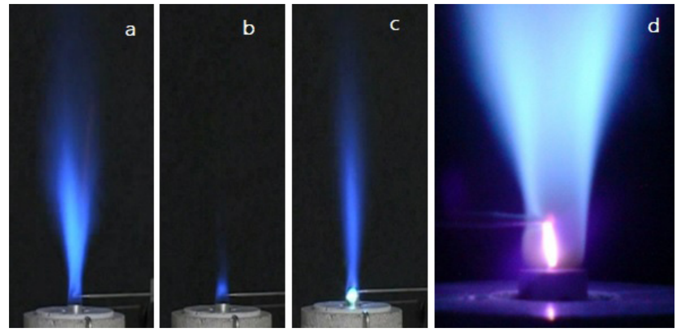

Figure 2. Propane-air flame at 1 bar (Mini-PAC burner studied at CentraleSupélec). (a) stable stoichiometric flame without plasma. (b) lean flame near the extinction limit, without plasma. (c) same lean flame stabilized by NRP discharge (10 ns pulses at 30 kHz). The average electric power of the NRP discharge is 75 W, which is only 0.7% of the power of the flame (11 kW here). (d) Close-up view of the discharge. Images: CentraleSupélec.

new methods to control the thermo-chemical processes of radicals and NOx production. Second, although PAC has been successfully demonstrated in laboratory-size combustors, the scale up to industrial, high-power combustors (100 kW-10 MW) remains uncharted territory.

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Suggested Reading:

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Christophe Laux is a professor of Mechanical and Aerospace Engineering at CentraleSupélec, University Paris Saclay, France. He received his Ph.D. in Mechanical Engineering at Stanford University in 1993, worked as a research scientist at Stanford until 2002, and then joined CentraleSupélec in 2003, where he leads the Nonequilibrium Plasma group of the EM2C laboratory (CNRS). He is an expert on fundamental studies of plasma discharges, chemical kinetics, radiation, and optical diagnostics for energy, environmental and aerospace applications. He recently started an ERC-funded research program to reduce the pollutants emitted by hydrogen and sustainable fuels. He is a Fellow of the American Institute of Aeronautics and Astronautics (AIAA).