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Effects of plasma assisted combustion on pollutant emissions of a premixed flame of natural gas and air

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ABSTRACT

The recently increasing interest in plasma assisted combustion is mainly motivated by new possibilities for ignition and flame stabilization, in addition to pollutant emission reduction and control. In a chemically active environment, the plasma generates radicals, excited chemical species and ions, thus increasing the combustion process reaction rate. In this paper, the effect of plasma assisted combustion on pollutant emissions of a premixed flame of natural gas and air is investigated by using two gas analyzer systems to acquire a diversity of pollutant gases. The plasma is created by using a gliding arc discharge at the equivalence ratios of $\phi = 1.2$ and 1.4, with applied electrical power ranging between 220 W and 370 W. The use of a gliding arc discharge leads to a reduction in the emissions of hydrocarbons and carbon monoxide. Meanwhile, the carbon dioxide emissions increase due to a faster oxidation of carbon monoxide and the water concentration in the exhaust gases is reduced with the use of plasma at the expense of higher hydrogen generation.

1. Introduction

In the search for improvements in combustion technology, a great effort has been made in plasma assisted combustion [1–13]. The input electrical power is an additional heat source that leads to thermal effects such as the increase in reactivity. The presence of charged particles and an electric field also change the transport properties [1]. But, the most attractive effect is the radical pool generated by non-thermal plasmas. This increased amount of radicals and excited species gives rise to new chemical routes that affect ignition, flame and combustion [1,2,7,14].

To achieve these effects, it is necessary to choose from one of a number of different discharges. The gliding arc discharge [3,15–19], due its characteristics which lie between thermal and non-thermal plasmas [17,20], is an interesting choice for such a type of application. This discharge can promote kinetic effects, but also has thermal effects, particularly important for ignition [1,2].

As it is known, the combustion reactions depend strongly on the chain-branching; the rapid radical creation. These short-lived reactive species are the key to initiating, maintaining and eventually finishing reactions. If one considers a well-stirred mixture the combustion reactions are driven by kinetic chemistry and the kinetic medium is controlled by radicals. Lange [21] and Lange et al. [22] carried out studies regarding the dynamics of chemical processes in methane under a pulsed discharge. They found that the concentration of CH and C_2 radicals amounted to 10^{14} and 10^{15} radicals per cm^3 respectively (4% of all carbon atoms introduced into the system before the discharge). Another study developed by Sobczyński et al. [23] shows that the concentration of the excited hydrogen, H, reached 1.1×10^{13} radicals per cm^3. As discussed by Vega et al. [24] the hydrogen enrichment has a strong influence on the combustion behavior with regards to flame stability. In their research, the blow-off limit was extended from an air number of 1.67 without the plasma application to 2.01 with plasma.

The kinetic, thermal and transport effects generated by the plasma are some of the promising tools for combustion technology. Among the applications, emission control can be highlighted not only to control pollutants but also to selectively generate species that can be useful for some specific purpose. For example, in rich-quench-lean combustors, the species generated in the fuel rich zone are responsible for maintaining the combustion stability in the lean zone [25].

Thus, this research proposes the use of a non-equilibrium plasma, generated by a gliding arc discharge, for assisted fuel-rich combustion of natural gas, with the objective of studying the fundamental aspects of the process, in particular, how the electri-

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cal discharge chemically affects the combustion process, through pollutant emission gas analysis.

Given this proposal, an analysis of natural gas (NG) plasma assisted combustion at equivalence ratios of $\phi = 1.2$ and 1.4 was performed. For this, the main parameter analyzed was the input electrical power, ranging in values from 220 W to 370 W. In addition, a comparison with the conventional combustion was carried out. The main aim is to observe the behavior of hydrocarbons (ethane, propane and CH_4), nitrogen oxides (NO, NO_2, NO_x), carbon monoxide (CO), carbon dioxide (CO_2), water vapor (H_2O) and molecular hydrogen (H_2) and thus to be able to monitor the characteristics of the chemical dynamics of the interaction of plasma discharges in natural gas and air mixture combustion.

2. Material and methods

The experimental test bench is shown in Fig. 1. The plasma reactor has the geometry called gliding arc in a tornado [16]. More details about this specific reactor can be found in [26]. The reactor was coupled to a post-reactor for the analyses of exhaust gases. The dimensions of the post-chamber are shown in Fig. 2. The plasma was generated by an AC power supply with characteristics found also in [26]. The signal (no load) is sinusoidal and the frequency is 60 Hz. The distance between electrodes is 0.4 mm.

In previous studies, this reactor was characterized regarding its electrical properties [27] and influence on flame [28]. The operation is in the high voltage and low-current regime. The RMS voltage is around 2–4 kV. A rough estimation of reduced electric field based on a voltage of 3 kV and a plasma column length of 15 mm (the variation in length is from 4 mm to about 20 mm) gives a value of 7.5 Td, without taking into account the gas heating, which means that the real value of the reduced electric field is higher. Zhu et al. [29] estimated an electron temperature of 0.8 eV (~9284 K) for a reduced electric field of 6 Td. Similar systems such as that reported by Korolev et al. [30] indicates gas temperature in the range of 1000–2000 K. Based on this information it can be pointed out that our plasma operates in non-thermal regime, i.e. electron temperature higher than gas temperature. Thus, kinetic effects must be more relevant than thermal effects.

The source gases, natural gas and pressurized air, were premixed and the mass flow rates were controlled by needle valves and measured by thermal mass flow controllers. The air mass flow rate was fixed at 0.79 g/s. The natural gas flow rates used were 0.056 g/s and 0.063 g/s, which correspond to fuel-to-air equivalence ratios of 1.2 and 1.4, respectively. In addition, the typical composition of the natural gas used in the present study is (% mol): 88.27% CH_4 (methane), 7.67% C_2H_6 (ethane), 1.55% C_3H_8 (propane), 0.16% i-C_4H_{10} (i-butane), 0.29% *n*-C_4H_{10} (*n*-butane), 0.08% i-C_5H_{12} (i-pentane), 0.065% *n*-C_5H_{12} (*n*-pentane), 0.075% C_6H_{14} (hexane), 0.01% C_7H_6, 1.19% N_2 (nitrogen) and 0.64% CO_2 (carbon dioxide).

Two different gas analyzers were used to acquire the concentration of the exhaust gases: an FTIR gas analyzer (MKS 2030) and an analytical gas analyzer (Emerson ROSEMOUNT Analytical MLT 4). Both of them are equipped with heated probes to avoid gas condensation of the sample gas; diaphragm pumps are used to conduct the sample to the devices.

The FTIR (Fourier Transform Infrared) gas analyzer provides real-time data with ppm/ppb or % sensitivity for >30 chemical species at the rate of 1 sample per second (1 Hz). It can perform analysis in gas streams containing up to 30% water. In fact, it is able to measure most molecules except for N_2, H_2 and O_2, i.e. molecules without an intrinsic electric dipole moment.

The analytical gas analyzer (Emerson ROSEMOUNT Analytical MLT 4) uses multiple sensibility sensors for acquiring specific gases. In this specific case, the species CO, O_2, CO_2 and H_2 were measured by internal sensors with the respective principles: infrared, electrochemical, ultraviolet and thermo conductivity. The ana-

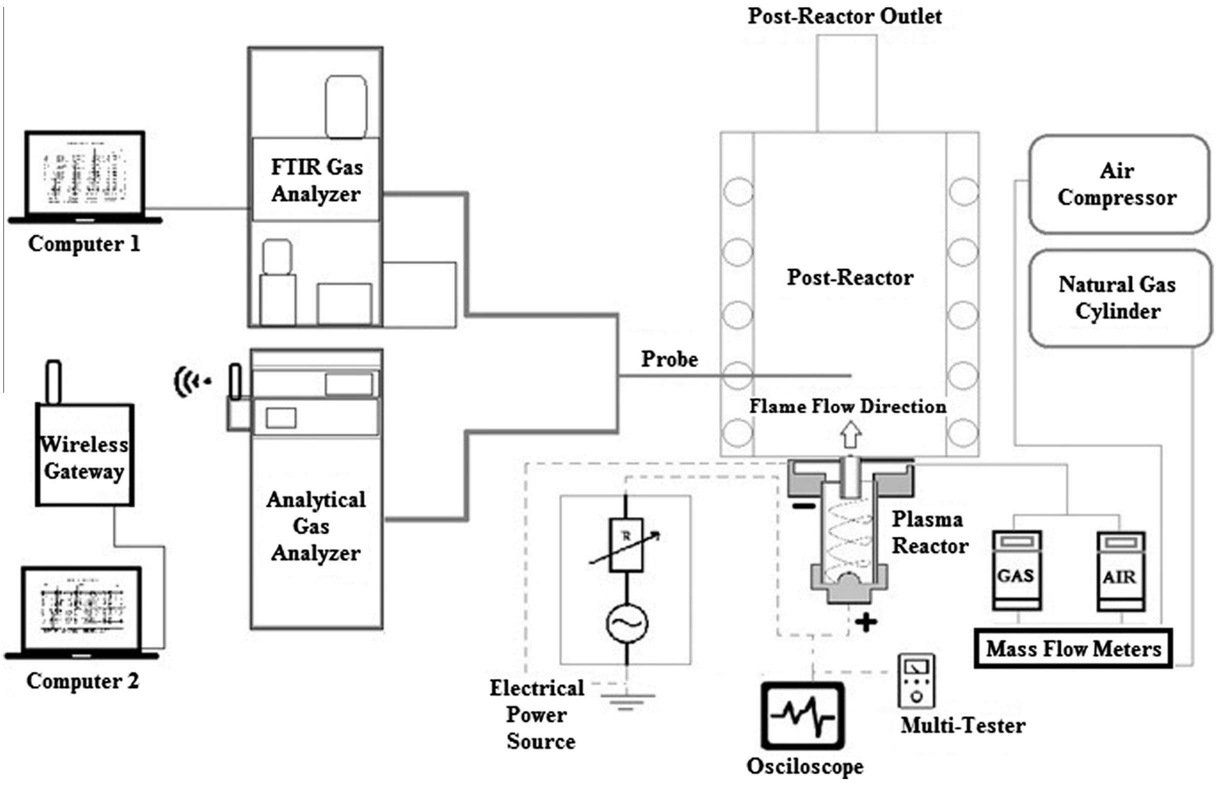

Fig. 1. Experimental setup.