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Nanosecond pulsed discharge in a propane–air mixture: Ignition and energy deposition

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Abstract

The study examined the possibility of using nanosecond pulse discharges as a new ignition and assisted combustion method to solve ignition and combustion stabilization problems encountered in new combustion technologies. To better understand how temperature and the presence of radicals affect nanosecond discharge ignitions, spatiotemporal profiles of rotational and vibrational $N_2(X)$ temperatures were measured through spontaneous Raman scattering in a lean propane–air mixture and compared with previous results obtained in air to obtain the space- and time-resolved measurements necessary to validate the kinetic modeling of the discharge in presence of hydrocarbons. The study aims to contribute to a better understanding of the initial ignition processes in stoichiometric mixture (first observed at 1 μs) and the rapid displacement of the flame front in propane–air mixtures. In the analyzed propane–air mixture, the gas heated slightly more rapidly than in air. This temperature increase might have occurred in the release of energy resulting from dissociation of propane due to quenching by metastable species. The presence of traces of CO confirmed this assumption. The energy transfer processes were identical in all other respects and occurred over the same time scales in air and in the propane–air mixture. Once the flame in the stoichiometric mixture was ignited, it propagated through a cylindrical channel whose diameter was identical to that of the volume of gas heated to above 900 K in the lean propane–air mixture. This early ignition and the spreading of the flame kernel demonstrate the combined effect of radicals and temperature on the nanosecond discharge ignition process. The resulting new database makes it possible to validate simulations of the vibrational kinetics involved in nanosecond discharges of a lean propane–air mixture and provides a first step toward modeling flame initiation.

Keywords: Plasma assisted combustion; Ignition; Nanosecond pulsed discharge; Propane; Spontaneous Raman scattering

1. Introduction

Ignition has become a key concern for many new combustion technologies because they involve highly diluted reactants, high-pressure conditions,

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and the need to facilitate re-ignition under various thermodynamic conditions ranging from low to high pressure. In view of these challenges, nanosecond discharges have been proposed as a possible method of ignition or assisted combustion [1,2], especially under lean conditions. The advantage of using such non-equilibrium plasmas is that they form highly reactive radicals, limit heat loss to the electrodes, and reduce the amount of heat dissipated by turbulence. Moreover, given the appropriate electrode geometry, nanosecond discharge ignition can occur at multiple sites [3]. Recent studies have focused on applying nanosecond discharges to assisted combustion and ignition [2–6]. Yet limited experimental data are available to determine the impact of radicals and temperature on the initiation of combustion. Thus, nanosecond discharge ignition remains an insufficiently understood process. Because nanosecond discharges are known to induce rapid gas heating, it is necessary to characterize the energy transfer processes that occur after the pulse discharge (e–V, V–V, and V–T energy transfers) to better understand the processes involved in nanosecond discharge ignition. A previous study used spontaneous Raman scattering (SRS) to investigate the kinetics involved in the energy transfers occurring with discharge processes in air [7–9]. A spatiotemporal analysis of the rovibrational distribution function of $N_2(X)$ and $O_2(X)$ molecules observed during the post-discharge phase has demonstrated that the amount of deposited energy was divided into different storage modes and that the dissociation of oxygen molecules resulted in the substantial production of oxygen atoms (33%) [9]. A similar analysis of a propane–air mixture was performed in the present study: spatiotemporal temperature profiles were obtained for a lean nonflammable propane–air mixture ($\varphi = 0.4$) to characterize the energy deposition process that occurs in hydrocarbon–air mixtures. First, a nonflammable mixture was analyzed to validate the plasma kinetics of a long post-discharge phase while excluding the influence of the combustion-heat release that occurs once the mixture ignites. Then, the same setup (electrodes and power supply) was used to ignite a stoichiometric flame in a constant volume chamber. The temperatures of the lean mixture were qualitatively compared with the flame observed in the stoichiometric mixture. Once the flame ignited in the stoichiometric mixture, it propagated through a cylindrical channel whose diameter was identical to that of the volume of gas heated to above 900 K in the lean propane–air mixture. The observed early ignition and the spreading of the flame kernel demonstrate the combined effect of radicals and temperature on the nanosecond discharge ignition process.

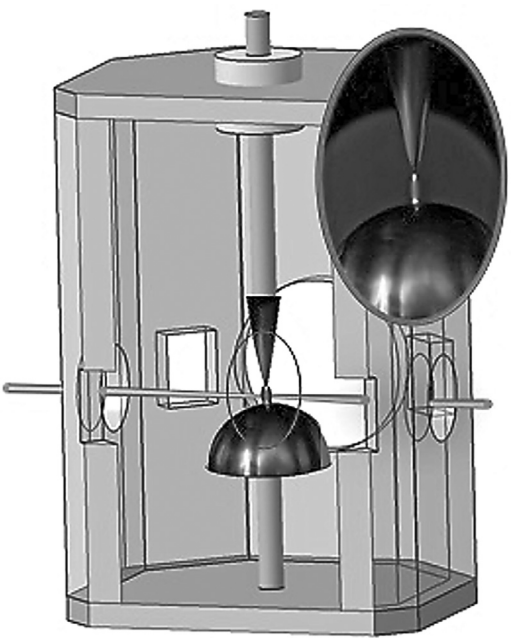

Fig. 1. Overview of the discharge setup.

2. Experimental setup

The SRS experimental setup has been described in detail elsewhere [10], and only a short summary is given here.

2.1. Discharge

The discharge setup (Fig. 1) consisted of a pin-to-plane geometry with an electrode gap of 6.5 mm and a tip curvature radius of 100 μm. The discharge was generated in a metal chamber with openings for an optical access and gas inlets. The chamber was filled either with air or with a propane–air mixture (equivalence ratio of $\varphi = 0.4$). A high-voltage generator (FID technology) was used to apply a positive high-voltage (HV) pulse of 25 kV to the pin electrode at a repetition rate of 10 Hz. The high-voltage pulse duration was 25 ns with a rise time of 5 ns [8]. Based on the current and voltage waveforms, the amount of deposited energy was estimated at 20 mJ per pulse [8] and was identical in air and in the lean propane–air mixture. The short pulse duration combined with the short rise time and the high amplitude of the HV pulse allows the generation of a high-energy repeatable elementary discharge without transition to arc regime. The concurrently decreasing current and HV pulse confirmed this assumption. The experimental configuration (tip radius, HV rise time, HV amplitude, electrode spacing) allowed the

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