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# Spark discharge ignition process in a spark-ignition engine using a time series of spectra measurements

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## Abstract

The spark discharge ignition process was investigated using simultaneous temperature measurements of the spark discharges and the initial flame kernel. We were able for the first time to measure a time series of emission spectra from the spark discharge and initial flame kernel inside a spark-ignition engine using a spectrometer coupled with a spark plug and optical fiber. The plasma vibrational temperature of the spark discharge can be measured using time series emission spectra from the electrically excited CN* violet band system. The gas rotational temperature of the initial flame kernel can also be measured using emission spectra from OH* radicals (P and R branches). Simultaneously, visualization of the spark discharge and a time series of emission spectra inside a spark-ignition engine were performed under homogeneous mixture conditions, to eliminate the effects of stratification of temperature and mixture concentrations around the spark plug. We discuss thermal energy transfer from the spark discharge to the combustible mixture. The main conclusions that can be drawn from this study are as follows. CN* emission can be detected from the spark discharge, visualized using a high-speed camera during the arc discharge phase. Our results confirmed that the plasma temperature of the spark discharge was nearly 6800 K and that thermal energy was transferred from the spark plasma channel to the combustible mixture. The gas temperature of the initial flame kernel approached that of the adiabatic flame temperature.

*Keywords:* Spark-ignition engine; Spark discharge; Plasma temperature; Adiabatic flame temperature; Time series of emission spectra

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## 1. Introduction

Combustion is initiated from the electrical spark discharge produced between the spark plug electrodes close to the end of the compression stroke in a gasoline spark-ignition engine. A high-temperature plasma kernel formed by the spark discharge and energy transfer from the high-temperature plasma to the combustible mixture occurs around the spark plug [1,2]. The initial flame kernel created by the spark discharge becomes a propagating flame. Currently, lean-burn combustion and direct-injection spark-ignition engines are being developed to improve the thermal efficiency and reduce emission products. In these engines, it

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is quite important to prepare an appropriate stratified fuel mixture around the spark plug due to direct fuel injection inside the cylinder and a larger amount of recycled exhaust gas [3,4]. Moreover, very strong tumble motions have been formed to improve the flame propagation speed using a tumble control valve and a lower bore/stroke ratio [5]. When the tumble flow is damped and broken at the end of the compression stroke, stronger turbulence exists around the spark plug and enables a higher turbulent burning velocity for the premixed mixture through the cylinder. It is quite difficult to maintain stable combustion in ultra lean-burn spark-ignition engines under stronger tumble motion conditions. Stable ignition and growth of the initial flame kernel are practically important for higher performance of gasoline spark-ignition engines, especially in terms of thermal efficiency and exhaust emissions.

The spark discharge process can be divided into three phases: breakdown, arc discharge, and glow discharge [6,7]. During the breakdown phase, a highly conductive plasma channel is formed between the spark electrodes. All molecules in this spark channel are dissociated and ionized with a high plasma ‘electrical temperature,’ of up to 60,000 K. This plasma electrical temperature then decreases due to plasma cooling and recombination phenomena. Ionization and dissociation energy are transformed into thermal energy during plasma cooling. In the arc phase, the thin cylindrical plasma expands, due to heat conduction and diffusion, with a lower ionization level. Due to these energy transfers, the plasma temperature in the arc becomes limited to ~6000 K [1,6]. Following the arc phase, a glow discharge can be formed and maintained for several milliseconds due to the secondary coil in a conventional coil spark-ignition system. The glow discharge has lower power but higher energy, due to the long discharge time. Inside this spark channel, the combustible mixture is preheated, up to the adiabatic flame temperature. Chemical reactions are initiated by the high radical density region in the breakdown phase. After several tens of microseconds, the plasma temperature decreases, comparable to the adiabatic flame temperature. OH and CH radical emissions appear after ~100 μs due to the high energy of the glow discharge.

Some of authors have investigated the laser ignition process using high-speed imaging and spatially, temporally, and spectrally resolved emission spectrum measurements [8,9]. The results provided information about the different stages of laser-induced breakdown, with a specific focus on the transition from a flame kernel to a self-sustaining flame in a Bunsen burner. The impact of the level of radicals in the flame kernel was a critical parameter for the firing process, starting ~100 μs after the laser-induced breakdown. CN radical emission can be detected until 20 μs after the laser spark; however, OH radical emission can be detected from the laser spark to flame initiation, from 10 to 400 μs. OH radicals can exist in the laser-induced plasma and initial flame kernel. In the case of a flame, OH radical emission intensity increases after 300 μs due to OH radical production in the flame front. It is a simple transition from laser-induced plasma to the chemical reactions of a combustible mixture. However, the spark discharge is categorized into three phases: breakdown, arc, and glow phases. Energy transfer from the spark plasma to the combustible gas is a key phenomenon to obtain stable initial flame kernel formation. The thermal energy transfer from the spark discharge to the combustible mixture has been measured using a calorimeter [10,11]. A calorimeter can determine the spark efficiency using measurements of the transient pressure increase in a small constant-volume vessel. Just 2.5% of the primary energy of the primary circuit is transferred to the combustible mixture. It is quite important to increase the efficiency of the thermal energy transfer from the spark discharge to the combustible mixture. Moreover, we have to measure the energy transfer inside a firing spark-ignition engine. A calorimeter cannot be applied in a practical spark-ignition engine.

In this research, temperatures of the spark discharge and the initial flame kernel were measured using a time series of spectra obtained using an electron multiplying charge-coupled device (EMCCD) spectrometer (Newton EMCCD; Andor Technology PLC, Belfast, UK) coupled with a spark plug with an optical fiber to understand the ignition process of the spark discharge in a spark-ignition engine. A spark plug with an optical fiber has been developed to obtain the emission spectra from the spark discharge and flame kernel [12,13]. Simultaneously, visualization of the spark discharge and a time series of emission spectra inside the spark-ignition engine were performed under homogeneous mixture conditions, to eliminate the effects of stratification of temperature and mixture concentrations around the spark plug. The plasma vibrational temperature of the spark discharge can be measured using the emission spectra from the vibrational transitions of the electrically excited CN violet band system [14–18]. Aragón and Aguilera showed vibrational and rotational temperatures of laser-induced plasma from the emission bands of the $CN^*$ in the case assuming local thermodynamic equilibrium (LTE) [18].

We sought to estimate the plasma vibrational temperature using the emission spectra of $CN^*$ during the arc phase of the spark discharge. The gas rotational temperature of the initial flame kernel can also be measured using the emission spectra of OH radicals (P and R branches) during the glow phase and the initial flame kernel development [14,19,20]. $OH^*$ can be detected in both the spark channel and

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