

Visualization of Partially Premixed Combustion of Gasoline-like Fuel Using High Speed Imaging in a Constant Volume Vessel

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ABSTRACT

Combustion visualizations were carried out in a constant volume vessel to study the partially premixed combustion of a gasoline-like fuel using high speed imaging. The test fuel (G80H20) is composed by volume 80% commercial gasoline and 20% n-heptane. The effects of ambient gas composition, ambient temperature and injection pressure on G80H20 combustion characteristics were analyzed. Meanwhile, a comparison of the EGR effect on combustion process between G80H20 and diesel was made. Four ambient gas conditions that represent the in-cylinder gas compositions of a heavy duty diesel engine with EGR ratios of 0%, 20%, 40% and 60% were used to simulate EGR conditions. Variables also include two ambient temperature (910K and 870K) and two injection pressure (20MPa and 50MPa) conditions. Results show that the flame luminance of G80H20 decreases, ignition delay increases and ignition position moves downstream from the injector tip with increasing EGR ratio, decreasing ambient temperature and increasing injection pressure. The liquid spray length of G80H20 is much shorter than that of diesel under the same conditions. The flame luminance of G80H20 fuel decreased significantly when ambient oxygen concentration drops from 21% to 16.3% (EGR ratio: 20%). While 11.1% oxygen concentration (EGR ratio: 60%) is needed for diesel fuel to achieve a great drop in flame luminance. This is mainly because a separation of end of injection (EOI) and start of combustion (SOC) is more easily achieved with G80H20, since the ignition delay (2.7~4.5ms) of G80H20 is longer than that (1.2~2.3ms) of diesel.

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INTRODUCTION

In the last two decades, to meet the demands for high efficiency and low emission compression ignition engines, researchers have carried out extensive works on advanced combustion concepts in internal combustion engines, such as Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI) and Partially Premixed Combustion (PPC). These advanced combustion modes aim to reduce NO_x and PM emissions simultaneously, while retaining high efficiency with low fuel consumption. This is achieved by reducing the combustion temperature and prolonging the ignition delay to enhance fuel-air mixing before combustion.

Among the new combustion concepts, Partially Premixed Combustion (PPC) [1] lies between the conventional diesel combustion mode and HCCI mode. In PPC concept, the fuel/air mixture distribution is inhomogeneous before start of combustion (SOC) and combustion phase is well controlled by injection timing. The aim of combustion phase control of PPC is to achieve a separation between end of injection (EOI) and SOC [2]. Diesel PPC has been studied by many

researchers and the experimental results show that both NO_x and PM emissions can be reduced. But it requires high level EGR and low compression ratio, which results in low combustion efficiency and limited engine load range [1][3].

In order to separate EOI with SOC even at high loads, Kalghatgi proposed to inject gasoline in a compression ignition engine in 2006 [4] and the results were remarkable. The engine could achieve 1.21 g/kWh of NO_x, 0.36 of smoke FSN and 178 g/kWh of ISFC at 14.86 bar IMEP with 25% of EGR. Since 2006, gasoline PPC experiments have been conducted both in heavy duty and light duty diesel engines at Royal Institute of Technology [4][5], Lund University [6][7][8][9], University of Wisconsin [10][11] and University of Cambridge [12][13]. It is shown that when the engine is fueled with low CN fuels, low NO_x and PM as well as high efficiency can be obtained simultaneously from low to maximum load with double injection strategies. Meanwhile, high pressure-rise-rate and relatively high levels of CO and HC emissions remain to be improved. Computational investigations of gasoline PPC have also been carried out at University of Wisconsin [14][15]. The computational

optimization results of a heavy duty diesel engine fueled with conventional gasoline show that good thermal efficiency and low NO_x emission can be achieved at mid and high loads, but the ringing intensity and soot emission remain challenging at high-load conditions [15].

In recent years, PPC using low Cetane Number (CN) fuels, such as gasoline-like fuels, has drawn increasing attention. Because of gasoline-like fuel's high volatility and resistance to auto-ignition, they can mix with air sufficiently before SOC without using too much EGR. However, up to now, most of the researches focused on PPC engine performance, few studies concentrated on combustion visualization to give an insight into PCC combustion process.

The objective of this paper is to study the characteristics of partially premixed combustion of a gasoline-like fuel. Visualization of auto-ignition and combustion process was achieved using high speed imaging in a constant volume vessel. The effect of ambient gas composition, ambient temperature and injection pressure on flame luminance, ignition delay and liquid spray length of G80H20 was studied based on a comparison with diesel fuel.

EXPERIMENTAL SETUP

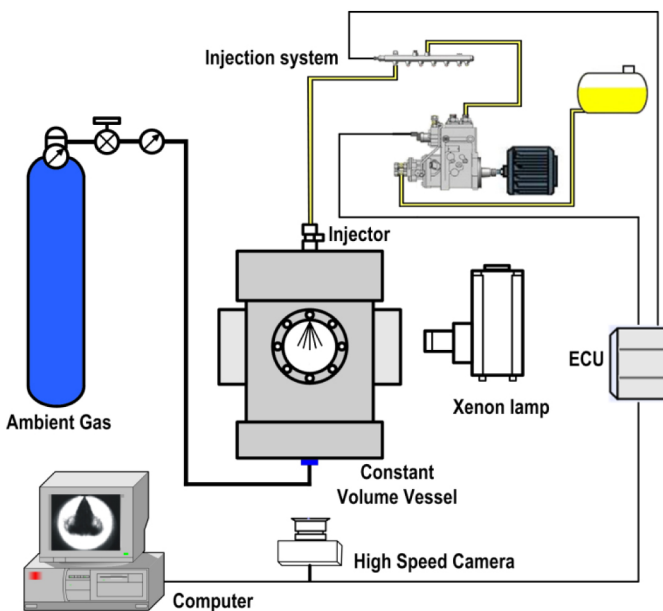


Figure 1. Experimental setup for high speed imaging of combustion process.

The high speed imaging experimental setup is shown in Fig. 1. The images were captured using a Phantom V7.3 high speed CMOS camera at a speed of 10000 frames per second and an exposure time of 98 μ s. The camera lens used here is a normal lens, not a UV lens. No filters and no image intensifiers were used in front of the camera during the experiments. The spatial resolution of the images was 256 $\times$ 512 pixels. A USHIO UXL-500SX xenon lamp was placed at one side of the constant volume vessel (see Fig.1) to illuminate the liquid-phase spray. And the xenon lamp was

switched on during all the measurements. Thus, the Mie-scattered light of the liquid spray could be captured by the camera. Then the time of start of injection (SOI) was known and ignition delay could be calculated.

CONSTANT VOLUME VESSEL

All the experiments in this paper are conducted in a high pressure high temperature constant volume vessel. The cross section of the vessel is depicted in Fig.2. The injector was mounted at the top of the chamber. The volume of the chamber is 0.017m³, including the space taken up by the heating cartridges. Optical access is provided via four quartz windows at each side, 100mm in diameter and 70mm thick. Two heating cartridges (2.6kW in total) are installed at the bottom of the chamber and it is separated with the testing region by a round metal plate (not included in Fig.2). The plate has lots of holes on it to let the air go through. Both the outside wall of the vessel and inside wall of the chamber are covered with thermal insulation materials to reduce heat loss. The temperature inside the chamber is monitored by five K-type thermocouples placed at different positions and the pressure is monitored by a pressure transducer. The maximum temperature that can be achieved is about 930K and the designed maximum pressure is 6MPa.

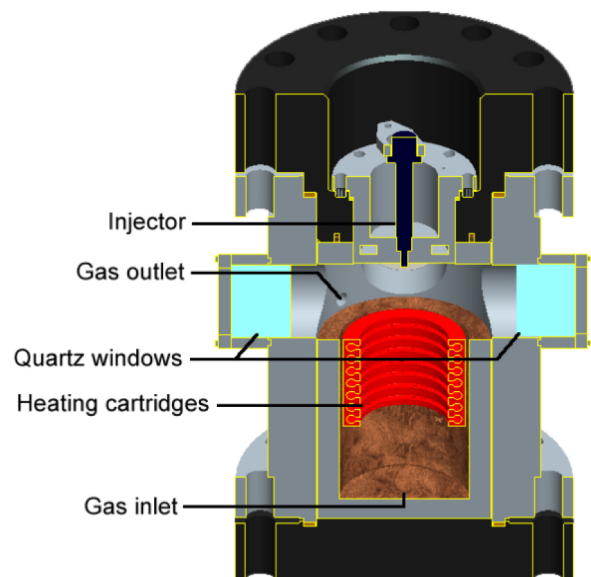


Figure 2. Sketch of cross section of the constant volume vessel.

The operation procedure is as follows. First, fill the chamber with gas of desired composition. Then the gas is heated with full power to a stable temperature, which means a thermal equilibrium is achieved. And during this heating process, the outlet valve keeps open. By this time the temperature is around 800K. After that, the outlet valve is closed and the inlet valve is opened to let the pressurized gas (the same kind of gas as the one in the first step) enter into the chamber, which makes the pressure and temperature in

the chamber rise quickly and also makes the temperature uniform. When the pressure gets to the target value, inlet valve is closed. Then the temperature starts to drop gradually. When a desired temperature is reached, fuel injection and the high speed camera are triggered. After data acquisition, the exhaust gas is released. The temperature and pressure traces are shown in Fig.3. Normally the first heating process takes fifty minutes and the following heating processes take thirty minutes each.

A temperature uniformity of $\pm 3\%$ can be achieved within a cylinder-shaped central region of the vessel after the vessel pressure reaches the target value up to the point of fuel injection. The radius and the height of this cylinder-shaped region are about 30mm and 80mm, respectively. The center of the region is 50mm right below the injector tip.

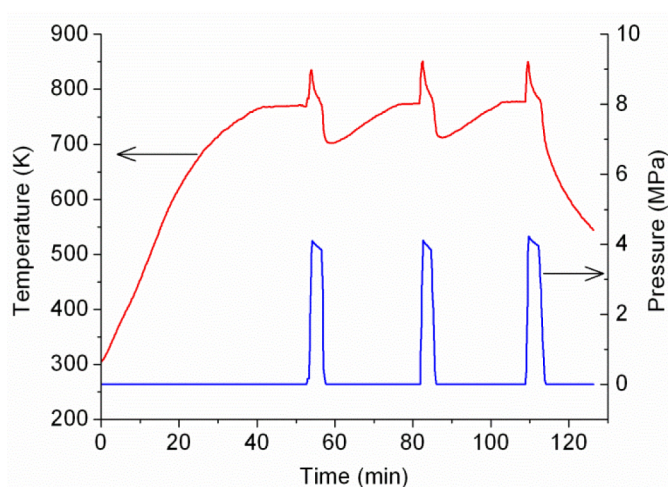


Figure 3. Temperature and pressure traces of typical heating processes.

INJECTION SYSTEM

A Bosch common rail injection system was used. The production 5-hole solenoid injector nozzle tip was replaced by a single-hole tip. The nozzle diameter is 0.168mm. The maximum injection pressure of the system is 160MPa. For the experiments presented here, two injection pressures, 20MPa and 50MPa, are used and the injection duration is 1600 μ s.

FUELS

A gasoline-like fuel (G80H20) composed by volume 80% commercial gasoline and 20% n-heptane was used. The addition of n-heptane aims to improve the fuel's auto-ignition behavior because the auto-ignition of the pure gasoline could not happen at an ambient temperature of 870K. Therefore, G80H20 instead of pure gasoline was used so that the combustion characteristics in a larger ambient temperature range could be investigated. Another consideration of using G80H20 is that it can be used to surrogate lower octane number gasoline. The addition of 20% (by volume) n-heptane

can lower the octane number of the fuel to about 75-80 RON. A previous study in Lund University [8] showed that for premixed CI combustion systems, the higher the octane number, the more problematic low load and high speed / high EGR operation becomes. Hence the optimum fuels might have lower octane number than in current practical gasoline fuels e.g. between 75 RON and 85 RON. A commercial diesel fuel was also used to make comparison with G80H20. The properties of n-heptane, gasoline and diesel fuel are listed in Table 1.

Table 1. Properties of n-heptane, gasoline and diesel fuel

	n-heptane*	Gasoline	Diesel
Density@20°C (kg/m ³)	632	755.4	839.3
CN	~55	---	52.6
RON	0	94.4	---
MON	0	82.7	---
LHV (MJ/kg)	44.56	43.5	42.9
Aromatics (v %)	0	35.5%	29.6%
T10 (°C)	---	59.7	214.8
T50 (°C)	---	107.3	266.1
T90 (°C)	---	160.2	333.6

*The properties of n-heptane are quoted from reference [16].

TEST CONDITIONS

The test conditions of this work are shown in Table 2. Variables include the ambient gas composition, ambient temperature and injection pressure. Data was collected at two ambient temperatures, 870K and 910K, at two injection pressures, 20MPa and 50MPa, and with four ambient gas compositions. These four kinds of ambient gas represent the in-cylinder gas compositions of a heavy duty diesel engine (DongFeng X11) with EGR ratios of 0%, 20%, 40% and 60%, respectively. The 4MPa (about 900K) conditions are to represent a case with early injection with a compression ratio of 17.2, corresponding to about 2.1 bar inlet pressure and 380K inlet temperature. And the corresponding SOI (start of injection) time is about -24 CAD (24 CAD BTDC). The fuel injected into the chamber is 6.9 mg in one injection event with the single-hole injector at 20MPa injection pressure. Then a fuel amount of 55.2 mg (6.9*8) roughly corresponds to 5.4 bar IMEP (1900r/min) for the DongFeng X11 engine.