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Experimental investigation of atomization and combustion characteristics of high-pressure pulse sprays

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ABSTRACT

This study investigated the effect of fuel injection pressure (20–80 MPa) on atomization and combustion characteristics using a stationary combustor with an intermittent supply of liquid fuel. In the atomization experiments, spray tip penetration and spray width increased, and the Sauter mean diameter of droplets decreased with an increase in the fuel injection pressure. In the combustion experiments, the OH emission intensity and combustion gas temperature upstream of the furnace increased with the fuel injection pressure, whereas nitrogen oxides emissions were reduced. The results demonstrate that high-pressure pulse spray combustion can reduce NO_X emissions and enhance the combustion load by an increase in the fuel injection pressure.

1. Introduction

Pulse combustion, which produces an intermittent flame by an intermittent supply of fuel or air, is one of the combustion technologies used in stationary combustors. Pulse combustion can reduce nitrogen oxides (NO_X) emissions by temporal variation of the distribution of fuel concentration in a combustion chamber. Keller and Hongo [1] conducted pulse combustion experiments with methane–air premixed gas in a Helmholtz-type pulse combustor and indicated that the rapid mixing of combustion gas with residual gas leads to decreasing NO_X emissions. This was also reported by Williams et al. [2]. In addition, McQuay et al. [3] showed that NO_X emissions can be reduced by the improvement of atomization and the enhancement of air–fuel mixing in an ethanol spray flame in a Rijke-type pulse combustor. Paschereit and Gutmark [4] also performed pulse combustion experiments with methane, which was supplied by controlling an inlet valve to stabilize premixed combustion, and investigated the combustion characteristics. As shown below, studies on the intermittent supply of gaseous fuel or air have been widely observed, but those on the intermittent supply of liquid fuel are rare for a stationary combustor. Furthermore, the combustion emission characteristics of pulse spray have never been investigated. For example, although Yu et al. [5] conducted pulse ethanol spray combustion experiments in a dump combustor, they focused on the shape of the spray and flame. Coen et al. [6] reported the measurement of carbon monoxide (CO) and NO_X emissions from pulse spray combustion in a gas turbine combustor. In their work, five-sixths of the fuel was injected continuously because their main interest was active control of combustion instability, and the continuous supply of fuel mostly affects combustion characteristics with a pulse spray.

On the other hand, a high-pressure fuel injection system (i.e., a common-rail system that can intermittently supply liquid fuel) is used for diesel engines. The split fuel injection is useful in the inhibition of combustion emissions [7,8]. Moreover, spray dispersion [9,10], mean droplet diameter [9], and combustion characteristics [11,12] of the spray have been investigated. The dispersion and Sauter mean diameter (SMD) of a high-pressure spray injected in high ambient pressure with a 5-hole injector were measured by Tonini et al. [9]. They reported that the increase in the fuel injection pressure enhanced spray dispersion and decreased the SMD. This trend was also reported by Suh et al. [10] who investigated the atomization characteristics of a high-pressure spray with a 6-hole piezo injector. Ye and Boehman [12] performed high-pressure spray combustion experiments in the combustion chamber of a diesel engine and suggested that fuel injection pressure significantly affects combustion emissions. As reported here, much research on spray combustion in diesel engines has been conducted. Inside the engine chamber, supplied air is compressed and expanded adiabatically; hence the pressure range is from 0.5 to 8 MPa, and the temperature change is from 330 to 900 K [8]. This variation in pressure and temperature inside the engine chamber influences the combustion characteristics [8,12], and the variation is over 10 times larger than that in a stationary combustor chamber [1]. Therefore, the combustion characteristics of a high-pressure pulse spray with a common-rail system in a stationary combustor can differ from those in a diesel engine.

In the present study, liquid fuel was intermittently injected to reduce NO_X emissions in a stationary combustor with various fuel injection

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pressures. To investigate the effect of the fuel injection pressure on spray dispersion and SMD, high-pressure pulse spray was formed with a common-rail system at atmospheric pressure and room temperature. Furthermore, the spray was combusted in a stationary combustor, and the effect of the fuel injection pressure on OH radical chemiluminescence emission intensity, combustion gas temperatures, and outlet gas concentrations was investigated.

2. Experimental

2.1. Atomization experiments

Fig. 1 shows the experimental setup for the atomization experiments. The solenoid injector in the common-rail system had one hole that was 0.21 mm in diameter. The experimental conditions are listed in Table 1. Oscillation frequency is injection frequency per second (as shown in Fig. 2), and fuel flow rate is the amount of injected fuel per minute. At each fuel injection pressure, the injection current was controlled to maintain a constant flow rate. The sprays were recorded by a high-speed camera (FASTCAM SA3, PHOTRON LIMITED) with a resolution of 256 × 512 pixels and a frame rate of 10 kHz. Metal halide lamps were used for light source. Spray tip penetration and spray width were calculated by image analyzer software (WinROOF version 6.1.0, MITANI CORPORATION). The thresholds of the luminosity values were calculated by the Otsu method [13], and the pixels with a brightness value larger than the threshold were classified as spray. The spray widths were measured as the average of the maximum vertical chord length at a certain time after the fuel injection. The spray tip penetrations were measured as the average of the maximum axial distance from the nozzle tip to the leading droplet pixel. Droplet diameters were measured by a particle size analyzer (Spraytec, Malvern Instruments Ltd) at 200 mm downstream from the nozzle tip, and the Sauter mean diameters (SMDs) of droplets were then calculated. These measurements were performed ten times for each condition.

2.2. Combustion experiments

Figs. 3 and 4 show a schematic diagram of the experimental setup and experimental combustion furnace, respectively. The nozzle tip of the common-rail system was centered at the inlet of the furnace. The sampling ports were located at central axial distances of 308, 408, 508, and 683 mm from the inlet. Before the experiments were performed, the inner wall of the furnace was heated. The wall temperature measured at the axial distance of 308 mm was around 1270 K. The injection conditions were the same as the atomization experiments (Table 1). The total excess air ratio was set to 1.2. Steady spray combustion, which was produced by continuous supply of fuel and air, was tested to compare with the high-pressure pulse spray combustion. The common-rail system was, however, difficult to supply fuel continuously. The steady spray was obtained by a hollow cone nozzle (spray angle 30°, Danfoss Hago Inc.). The fuel and air flow rate of the steady spray combustion was the same as the high-pressure pulse spray combustion. The fuel sprays were ignited by thermal radiation from the furnace wall. Since the wavelength of OH radical chemiluminescence exists around 310 nm [14], flame light through a band pass filter at 310 nm was translated into current by a photomultiplier tube, similar to that described by Mancaruso et al. [15]. To obtain the OH radical emission intensity, the current values were measured at axial distances of 308 and 683 mm from the inlet. Noise of the current was eliminated by a low-pass filter at 500 Hz. To improve the precision of temperature measurement, a suction pyrometer probe equipped with a B-type thermocouple was used to measure the combustion gas temperature at central axial distances of 308–683 mm and at radial distances of 0–135 mm at the axial distance of 308 mm. The gas suction rate in the protective tube of the suction pyrometer was 25 L/min at room temperature. Note that the protective tube was alumina because Matsushita et al. [16] indicated that the temperature in a furnace is decreased with a water-cooled tube. To measure the emission characteristics, exhaust gas was sucked by a sampling probe at the center of the outlet. The O_2, CO, CO_2, and NO_X concentrations in the exhaust gas were measured by a portable gas analyzer (testo350, TESTO, INC.), and the NO_X concentration was corrected at 0% O_2 concentration. The combustion gas temperature and exhaust gas concentration were recorded for a period of 20 s. For each condition, the measurements were performed three times, and the maximum values of each measurement were averaged.

Table 1
Experimental conditions of atomization.

Fuel		Commercial diesel
Fuel flow rate	[L/min]	0.05
Oscillation frequency	[Hz]	200
Injection pressure	[MPa]	20, 40, 60, 80
Current time	[ms]	0.67, 0.35, 0.28, 0.16
Nozzle diameter	[mm]	0.21

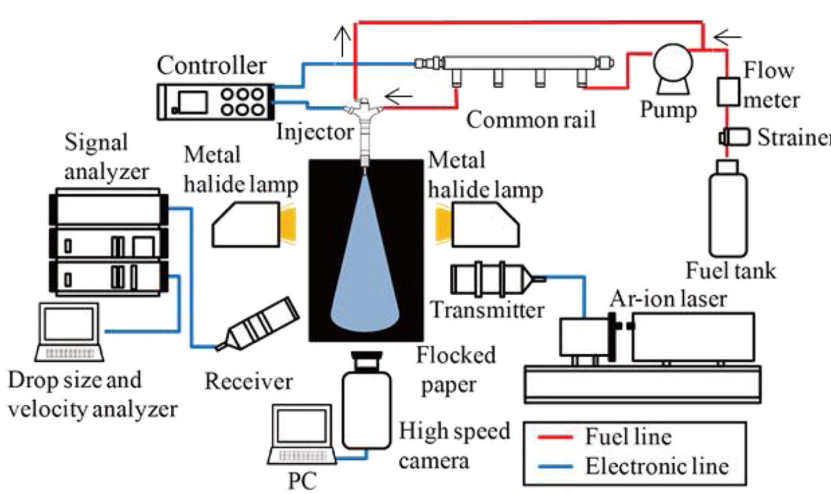

Fig. 1. Setup of the atomization experiments.