1 Experimental Investigation of Atomization and Combustion Characteristics of High-Pressure Pulse
2 Sprays
3
4 Satoki Yokoi^{a*}, Shota Sugawara^a, Ryuichi Sagawa^a, Yasuhiro Saito^a, Yohsuke Matsushita^a, Hideyuki
5 Aoki^a
6 ^aDepartment of Chemical Engineering, Graduate School of Engineering, Tohoku University, 6-6-07
7 Aoba, Aramaki, Aoba-ku, Sendai, Miyagi 980-8579, Japan,
8 * Corresponding author. Tel: +81 22 795 7251.
9 E-mail address: yokoi@dc.tohoku.ac.jp
10

11 Abstract

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

20

21 keywords: Spray combustion, Spray penetration, NO_x reduction, Pulse spray, Common rail

22

23 1. Introduction

24

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

45 On the other hand, a high-pressure fuel injection system (i.e., a common-rail system that can
46 intermittently supply liquid fuel) is used for diesel engines. The split fuel injection is useful in the
47 inhibition of combustion emissions [7, 8]. Moreover, spray dispersion [9, 10], mean droplet diameter
48 [9], and combustion characteristics [11, 12] of the spray have been investigated. The dispersion and
49 Sauter mean diameter (SMD) of a high-pressure spray injected in high ambient pressure with a
50 5-hole injector were measured by Tonini *et al.* [9]. They reported that the increase in the fuel
51 injection pressure enhanced spray dispersion and decreased the SMD. This trend was also reported
52 by Suh *et al.* [10] who investigated the atomization characteristics of a high-pressure spray with a
53 6-hole piezo injector. Ye and Boehman [12] performed high-pressure spray combustion experiments
54 in the combustion chamber of a diesel engine and suggested that fuel injection pressure significantly
55 affects combustion emissions. As reported here, much research on spray combustion in diesel
56 engines has been conducted. Inside the engine chamber, supplied air is compressed and expanded
57 adiabatically; hence the pressure range is from 0.5 to 8 MPa, and the temperature change is from 330
58 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 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

Figure 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 Figure 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.

Figure 1 Setup of the atomization experiments.

Figure 2 Injection rate vs time.

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

2.2. Combustion experiments

Figures 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 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 degree, 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 O₂, CO, CO₂, 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% O₂ 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.

Figure 3 Setup of the combustion experiments.

Figure 4 Schematic diagram of the combustion furnace.

3. Results and discussion

3.1. Atomization characteristics

3.1.1. Spray penetration and width

Because spray dispersion is an important factor in exhaust gas concentrations [7, 8], the spray tip penetration and spray width were measured for unburned sprays. Figure 5 presents the spray tip penetration measurements after the start of fuel injection for each fuel injection pressure at atmospheric pressure and room temperature. The spray tip penetrations at the same elapsed time increased with the fuel injection pressure, which is consistent with previous research [9, 10]. This indicates that fuel injection pressure significantly affects early spray development. Figure 6 shows the spray width after the start of fuel injection at each fuel injection pressure. The spray widths at each elapsed time increased with fuel injection pressure. The increase in spray width was likely caused by the turbulence of gas flow due to the exchange of momentum between the spray and

152 ambient gas. Hence, higher fuel injection pressure leads to enhanced spray dispersion and to an
 153 increased rate of entrainment.
 154

155
 156 Figure 5 Relationship between spray tip penetration and time at each injection pressure.

157
 158 Figure 6 Relationship between spray width and time at each injection pressure.

159

160

161 3.1.2. Sauter mean diameter

162

163 Since an increase in the heat transfer area of droplets leads to enhanced evaporation of a spray,
 164 Sauter mean diameters (SMD) were measured to estimate the effect of fuel injection pressure on
 165 evaporation. Figure 7 shows the SMD at 200 mm downstream from the injector nozzle tip. The SMD
 166 slightly decreases with an increase in the fuel injection pressure, and these results are in agreement
 167 with a previous observation [9] at high ambient pressure. This can be explained by the increased
 168 injection velocity caused by the increased fuel injection pressure. The results suggest that spray
 169 evaporation is enhanced by increasing fuel injection pressure.

Figure 7 Variation of Sauter mean diameter in relation to injection pressure.

3.2. Combustion characteristics

3.2.1. Chemiluminescence of OH radical

The OH radical is an intermediate of the combustion reaction and correlates with the intensity of the reaction [17]. Accordingly, OH emission intensity measurements have been widely conducted to investigate ignition and extinction of flames in stationary combustors [4, 14, 18] or diesel engines [11, 15, 19]. In the present work, the intensities were measured at axial distances of 308 and 683 mm, as shown in Figure 8. At an axial distance of 308 mm, the peaks and measurement time of the intensity increased with the fuel injection pressure. On the other hand, at 683 mm they decreased with an increase in fuel injection pressure. This is because both air entrainment and spray evaporation in the early stages of spray development increase with the fuel injection pressure, and the amount of burned fuel increases near the injector. Hence, the extinction of the flame is accelerated, and the tendencies of the abovementioned peaks and measurement time are reversed downstream of the furnace. At an injection pressure of 80 MPa, OH emission was almost continuously detected, as shown in Figure 8 (a). This suggests that subsequent evaporating spray catches up with the combustion region formed by the previous injection. Then, vaporization of the spray might be enhanced by its mixing with burned gas.

Figure 8 Time series of OH radical chemiluminescence at axial distances of 308 mm (left) and 683 mm (right) from the inlet.

3.2.2. Combustion gas temperature

Combustion gas temperature was measured to quantify the combustion characteristics in the furnace. Figure 9 (a) shows the combustion temperatures along the central axis in the case of high-pressure pulse spray combustion and steady spray combustion. At fuel injection pressures of 40–80 MPa, the highest combustion temperature was recorded at an axial distance of 308 mm. This indicates that most of the fuel burned out between 0 and 308 mm. In the case of the fuel injection pressure of 20 MPa, the highest combustion temperature was recorded at an axial distance of 408 mm. This could be caused by declining the spray dispersion and entrainment rate. In addition, the maximum combustion gas temperature increased with the fuel injection pressure. This trend is similar to previous research for engines [12]. The results of combustion gas and OH emission intensity reveal that an increase in the fuel injection pressure enhances the combustion reaction near the injection nozzle. As shown in Figure 9 (b), the combustion gas temperatures beyond a radial direction of 60 mm were around 1400 K at an axial distance of 308 mm. This suggests that spray dispersion at room temperature almost corresponds to combustion region when considering the width of the spray. At high ambient pressure and temperature, Dec [11] noted that the combustion region of diesel spray exists at the fuel spray periphery. In the present investigation, however, the highest temperatures at each fuel injection pressure were at the center axis. This could be a result of a relatively lean air–fuel mixture being produced in the whole spray because a longer time is required than that in an engine until ignition because of the mixing of the spray with cooler ambient gas.

220

(a)

(b)

221

222 Figure 9 Combustion gas temperature: (a) axial direction on the center axis and (b) radial direction at
223 308 mm downstream from the nozzle tip.

224

225

226 3.2.3. Exhaust gas concentrations

227

228 The O_2 , CO , CO_2 , and NO_x concentrations in the emission gas were investigated to elucidate
229 the emission characteristics of high-pressure pulse spray combustion. Differences in the O_2 and CO_2
230 concentrations, caused by changes in the fuel injection pressure, were not significant. Moreover, the
231 CO concentrations in this study were below the detection limit (<1 ppm); although in a diesel engine
232 [15] these are high due to the effect of quench caused by adiabatic dispersion. Therefore, the injected
233 fuel was completely burned in the furnace. The high combustion gas temperature, caused by the high
234 fuel injection pressure (Figure 9), led to an increase in thermal NO_x . Emissions of NO_x in a diesel
235 engine [12] also increase because of an increase in the fuel injection pressure. Interestingly, however,
236 the NO_x concentration decreased with an increase in the fuel injection pressure, as shown in Figure
237 10 (b). Previous research on pulse combustors [2] reported that the rapid mixing of combustion gas
238 with cold air, or cooler burned gas, leads to reduction of NO_x emissions because residence time in
239 the high temperature region decreases. Hence, thermal NO_x can be reduced because the higher
240 turbulent intensity of ambient gas (caused by higher fuel injection pressure) leads to rapid mixing of
241 combustion gas and cold air.

242

243
244

245

246 Figure 10 Combustion concentrations at different injection pressures: (a) O₂ and CO₂ concentration
247 and (b) NO_x concentration.

248

249

250 3.2.4. High-pressure pulse spray combustion model

251

252 Figure 11 shows a schematic description of high-pressure pulse spray combustion. This
253 conceptual model was conjectured from measurements of OH emission intensity, combustion gas
254 temperature, and NO_x concentration in the combustion experiments. In Figure 11 (a), fuel is injected
255 into ambient conditions and mixed with cold air. Concurrently, the spray and the air are heated by
256 thermal radiation from the furnace wall. Subsequently, droplets are vaporized and an air–fuel
257 mixture is produced, as shown in Figure 11 (b). This air–fuel mixture should be lean, as discussed in
258 Section 3.2.2, so that the burning of the mixture leads to the vaporization and ignition of residual
259 droplets inside the spray (Figures 11 (c) and (d)). Turbulence of the ambient gas enhances the mixing
260 of burned gas with cold air in Figure 11 (e). Hence, the residence time of high temperature gas
261 decreases. The subsequent spray mixes with cold air and catches up with burned gas in Figure 11 (f).
262 Then, vaporization and ignition of the spray might be enhanced by the burned gas, as shown in
263 Figure 11 (g).

264

Figure 11 High-pressure pulse spray combustion model based on the combustion experiments.

Overall, in a high-pressure pulse spray, the increase of fuel injection pressure should enhance the mixing of unburned fuel gas with ambient air because the amount of entrained gas in the spray increases with spray tip penetration and spray width, and with a decrease in droplet size; thereby enhancing the evaporation of fuel droplets (as shown by the SMD measurements). Consequently, in high-pressure pulse spray combustion, the higher fuel injection pressure leads to an increasing amount of burning fuel near the injector, and it is suggested that the combustion gas temperature upstream of the furnace increases. Although it has been widely observed that thermal NO_x increases with combustion gas temperature, NO_x concentration in high-pressure pulse spray combustion is reduced at high combustion gas temperatures. This can be explained by the reduction in residence time in the high temperature region since the higher fuel injection pressure enhances the mixing of combustion gas with ambient gas. Therefore, high-pressure pulse spray combustion can reduce NO_x emissions and enhance the combustion load.

4. Conclusion

In previous research, pulsed gas combustion has been shown to reduce nitrogen oxides (NO_x) emissions with temporal variation of the fuel concentration in the combustion chamber. However, the combustion emission characteristics of pulse combustion with liquid fuel have never been investigated. Hence, we applied a common rail to a stationary combustor and investigated the effect of fuel injection pressure on the characteristics of atomization and combustion.

In the atomization experiments, an increase in the fuel injection pressure increased spray dispersion and decreased the Sauter mean diameter. This suggests that the combustion reaction is

enhanced by the rapid mixing of fuel with air, due to the higher fuel injection pressure. In fact, the upstream OH emission intensity and combustion gas temperature were higher than those downstream of the combustor. The CO emissions in the high-pressure pulse spray combustion were much lower than in a diesel engine, and the high-pressure pulse spray combustion tended to be complete combustion. Also, the NO_x emissions were reduced with an increase in the fuel injection pressure. Therefore, high-pressure pulse spray combustion can reduce NO_x emission and enhance the combustion load because of the increase in the fuel injection pressure.

Acknowledgments

This work was supported by Naito Taisyun Science and Technology Foundation, JSPS KAKENHI Grant Number 22360318, and JST Research Seeds Quest Program, and carried out with the joint research program of the EcoTopia Science Institute. We appreciate Professor Ichiro Naruse, EcoTopia Science Institute of Nagoya University, for funding this work and Masakazu Shoji, Shizenkankyosangyo Co. Ltd., for his great contributions to the combustion experiments.

References

- [1] J.O. Keller, I. Hongo, Pulse combustion: The mechanisms of NO_x production, *Combustion and Flame*, 80 (1990), pp. 219–237.
- [2] T.C. Williams, G.K. Hargrave, C.P. Garner, V.I. Hanby, Inlet mixing and NO_x formation in a helmholtz pulse combustor, *Proceedings of the Combustion Institute*, 28 (2000), pp. 1289–1295.
- [3] M.Q. McQuay, R.K. Dubey, W.A. Nazeer, An experimental study on the impact of acoustics and spray quality on the emissions of CO and NO from an ethanol spray flame, *Fuel*, 77 (1998), pp. 425–435.
- [4] C.O. Paschereit, E. Gutmark, Combustion Instability and Emission Control by Pulsating Fuel Injection, *Journal of Turbomachinery*, 130 (2008), p. 011012.
- [5] K.H. Yu, T.P. Parr, K.J. Wilson, K.C. Schadow, E.J. Gutmark, Active control of liquid-fueled combustion using periodic vortex-droplet interaction, *Symposium (International) on Combustion*, 26 (1996), pp. 2843–2850.
- [6] J.M. Cohen, N.M. Rey, C.A. Jacobson, T.J. Anderson, Active Control of Combustion Instability in a Liquid-Fueled Low-NO_x Combustor, *Journal of Engineering for Gas Turbines and Power*, 121 (1999), pp. 281–284.
- [7] M.R. Herfatmanesh, P. Lu, M.A. Attar, H. Zhao, Experimental investigation into the effects of two-stage injection on fuel injection quantity, combustion and emissions in a high-speed optical common rail diesel engine, *Fuel*, 109 (2013), pp. 137–147.
- [8] M. Zheng, R. Kumar, Implementation of multiple-pulse injection strategies to enhance the homogeneity for simultaneous low-NO_x and -soot diesel combustion, *International Journal of*

327 Thermal Sciences, 48 (2009), pp. 1829–1841.

328 [9] S. Tonini, M. Gavaises, A. Theodorakakos, The role of droplet fragmentation in high-pressure
 329 evaporating diesel sprays, *International Journal of Thermal Sciences*, 48 (2009), pp. 554–572.

330 [10] H.K. Suh, S.W. Park, C.S. Lee, Effect of piezo-driven injection system on the macroscopic and
 331 microscopic atomization characteristics of diesel fuel spray, *Fuel*, 86 (2007), pp. 2833–2845.

332 [11] J.E. Dec, A Conceptual Model of DI Diesel Combustion Based on Laser-Sheet Imaging*, SAE
 333 Technical Paper 970873, (1997), pp. 1319–1948.

334 [12] P. Ye, A.L. Boehman, An investigation of the impact of injection strategy and biodiesel on
 335 engine NO_x and particulate matter emissions with a common-rail turbocharged DI diesel engine,
 336 *Fuel*, 97 (2012), pp. 476–488.

337 [13] N. Otsu, A Threshold Selection Method from Gray-Level Histograms, *Systems, Man and*
 338 *Cybernetics, IEEE Transactions on*, 9 (1979), pp. 62–66.

339 [14] J. Kojima, Y. Ikeda, T. Nakajima, Spatially resolved measurement of OH*, CH*, and C₂*
 340 chemiluminescence in the reaction zone of laminar methane/air premixed flames, *Proceedings of the*
 341 *Combustion Institute*, 28 (2000), pp. 1757–1764.

342 [15] E. Mancaruso, B.M. Vaglieco, Premixed combustion of GTL and RME fuels in a single cylinder
 343 research engine, *Applied Energy*, 91 (2012), pp. 385–394.

344 [16] Y. Matsushita, K. Sugawara, Y. Morozumi, H. Aoki, T. Miura, H. Tominaga, A Numerical
 345 Investigation of Temperature Measurement Error upon Insertion of a Suction Pyrometer into a
 346 Combustor, *KAGAKU KOGAKU RONBUNSHU*, 32 (2006), pp. 494–499.

347 [17] J. Kojima, Y. Ikeda, T. Nakajima, J. Furukawa, Chemiluminescence-Based Diagnostics for the
 348 Flame-Front Structure of Premixed Flames, *Transactions of the Japan Society of Mechanical*
 349 *Engineers Series B*, 69 (2003), pp. 482–489.

350 [18] Y. Ikeda, J. Kojima, T. Nakajima, F. Akamatsu, M. Katsuki, Measurement of the local
 351 flamefront structure of turbulent premixed flames by local chemiluminescence, *Proceedings of the*
 352 *Combustion Institute*, 28 (2000), pp. 343–350.

353 [19] V. Macian, R. Payri, S. Ruiz, M. Bardi, A.H. Plazas, Experimental study of the relationship
 354 between injection rate shape and Diesel ignition using a novel piezo-actuated direct-acting injector,
 355 *Applied Energy*, 118 (2014), pp. 100–113.