Auto-ignition characteristics of high-reactivity gasoline fuel using a gasoline multi-hole injector

Jianguo Du^a, Balaji Mohan^{a,*}, Jaeheon Sim^b, Tiegang Fang^c, William L Roberts^a

^a*Clean Combustion Research Center, King Abdullah University of Science and Technology, Thuwal, Makkah Province, Saudi Arabia*

^b*Fuel Technology Division, R&DC, Saudi Aramco, Dhahran, Eastern Province, Saudi Arabia*

^c*Department of Mechanical and Aerospace Engineering, North Carolina State University, Raleigh, NC 27695, United States*

Abstract

Gasoline compression ignition (GCI) engines have proven to be a highly efficient engine technology with reduced emissions. The high efficiency and reduced emissions of GCI engines heavily rely on the stratification of the fuel being injected directly into the cylinder through multi-hole injectors. Therefore, it is critical to understand the fuel stratification and auto-ignition behaviors of the fuels used in GCI engines. Thus, in this work, the auto-ignition characteristics of high-reactivity and low carbon gasoline fuel (RON 77) were studied in an optically accessible constant volume chamber. A customized high-pressure gasoline multi-hole injector was used. Reactive tests were performed at two different ambient pressures (20 and 30 bar), three different ambient temperatures (800, 900, and 1000K), three different oxygen concentrations (10, 15 and 21%) and three different injection pressures (100, 300 and 450 bar). The auto-ignition of fuel was achieved with varying ignition

*Corresponding author: balaji.mohan@kaust.edu.sa

delay based on the experimental conditions tested. It was found that the operating conditions profoundly influences the diffusion and partially-premixed combustion mode. For high ambient pressures, temperatures, oxygen concentrations, injection pressure, and combinations, diffusion combustion mode was observed, and partially premixed combustion mode was observed at lower ambient pressures, temperatures, oxygen concentrations, injection pressures, and their combinations.

Keywords:

ignition delay, diffusion combustion mode, partially-premixed combustion mode, low carbon fuel

1 Highlights

- Spray auto-ignition of gasoline multi-hole fuel injector was studied.
- Ignition delay times of high-reactivity low carbon gasoline fuel were measured.
- Effects of ambient temperature, pressure, oxygen concentration and injection pressures were investigated.
- Two different modes of combustion were observed.

1. Introduction

Gasoline compression ignition (GCI) engines are gaining popularity among the engine community due to its higher thermal efficiency and relatively lower emissions [1, 2]. GCI engines have significant advantages of achieving both diesel-like high thermal efficiency and gasoline-like low emissions. Typical

Gasoline with low reactivity and higher octane numbers can be used in GCI engines. However, high-reactivity gasoline-like fuels in the same gasoline boiling range are more desirable for auto-ignition by compression. Many fuels with different physical and chemical properties, such as distillation curves, chemical compositions, and ignition quality, have been considered in the previous works. Some of the fuels considered are conventional gasolines [3, 4], diesel [5], gasoline/diesel blends [6], binary and ternary fuel blends [7] and low-octane gasoline fuels [8, 9, 10]. Kolodziej et al. [11] analyzed GCI engine performance and emissions using fuel ranging from octane numbers of 60-91. They found that RON 80 fuel showed promising results in GCI engines. Recently, Jiang et al. [12] studied the effects of exhaust gas recirculation and fuel octane number on the performance and emissions of GCI engines. It was reported that the PRF70 fuel provided the highest indicated thermal efficiency of 47% under medium load conditions. Therefore, a new fuel was formulated with RON 77 in the objective of developing a fuel with RON 80 and gasoline-like density and boiling characteristics for GCI engine applications. The auto-ignition behavior was studied using shock tube and rapid compression machine for this RON 77 fuel and was reported recently by Al-Abbad et al. [13]. This GCI RON 77 fuel is a customized mixture of Saudi Aramco hydrotreated light naphtha (50% vol.), heavy naphtha (25% vol.), and a high-octane reformat (25% vol.). The properties of the GCI RON 77 fuel are shown in Table 1.

In compression ignition engines, the combustion completeness depends on the fuel injection process and careful matching of the air-fuel mixture because the fuel stratification and distribution inside the cylinder are governed

Table 1: Properties of GCI RON 77 fuel [13]

RON	77
MON	73.9
Density (kg/m^3)	720.7
Average MW	89.97
C/H	5.93
Paraffins (% mol.)	22.4
iso-paraffins (% mol.)	41.2
Naphthenes (% mol.)	15.6
Aromatics (% mol.)	20

38 by the spray characteristics and atomization [14]. Raman et al.[15] studied
39 the combustion stratification of naphtha fuel in partially premixed combus-
40 tion (PPC) mode using optical engines and found that the start of injection
41 and dilution of intake affects the fuel-air mixture and emissions such as NO_x
42 and soot formation. Goyal and Kook [16] studied the ignition process of GCI
43 combustion in a small-bore optical engine and found that the ignition pro-
44 cess shows higher sensitivity to mixture stratification and local equivalence
45 ratio distributions. Wang et al. [17] studied the auto-ignition of naphtha,
46 primary reference fuels (PRF), gasoline, and its surrogate and found out that
47 ignition delay difference is more significant if the ambient temperature was
48 below 750 K and the difference becomes insignificant when the ambient tem-
49 perature was above 750 K. Recently, the spray characterization of this GCI
50 RON 77 fuel in comparison with that of certification E10 gasoline fuel was
51 reported. Both the fuels showed very similar liquid and vapor penetration

under no EGR to high EGR conditions [18, 19]. Further, the fundamental experimental data on fuel spray combustion processes are essential for chemical mechanism development and validating numerical simulations [20]. Some studies have been reported in the literature using optical engine diagnostics on spray combustion process for conventional gasoline direct injection (GDI) engines [21, 22, 23], conventional compression-ignition engines [24, 25, 26] and partially premixed combustion engines [26, 27]. However, according to Baert et al. [28] optical engines are limited in peak pressure and temperature due to design constraints which restricts them to be used for real engine conditions. Thus in this study, the auto-ignition characteristics of GCI RON 77 fuel were investigated using a gasoline multi-hole injector in a constant volume combustion chamber. A wide range of experimental conditions which includes two different ambient pressures (20 and 30 bar), three different ambient temperatures (800, 900, 1000 K), three different injection pressures (100, 200, and 450 bar) and three different oxygen concentration (10, 15, 21%) representing the in-cylinder conditions of GCI engines were studied.

2. Experimental set-up

Experiments were conducted in a pre-burn type constant volume combustion chamber (CVCC) at KAUST Spray Lab. The chamber has six windows out of which two windows are used for optical purposes and one for fixing the injector. The 60 mm thick quartz window gives a 100 mm diameter optical access. The CVCC is capable of handling peak pressure up to 150 bar. The schematic of the CVCC system is shown in Fig. 1. Pre-mixed gas preparation, pre-burn initiation, fuel injection activation, and high-speed imaging are

76 automated through in-house LabVIEW program such that run to run varia-
 77 tions due to the anthropic operation is minimized. Pre-burn gas components
 78 were firstly mixed in an accumulator and then pushed by high-pressure ni-
 79 trogen gas into the CVCC. The gas mixture was ignited by a spark plug such
 80 that high pressure and high temperature is formed. Due to heat loss, pre-
 81 burn gas product pressure and temperature will decrease with time. Then
 82 the injection is triggered with a carefully selected delay after spark ignition,
 83 such that a desired ambient gas pressure and the temperature is achieved. A
 84 pressure transducer (Kistler 6041B) coupled with a charge amplifier (Kistler
 85 5018) was utilized to measure the transient chamber pressure during the en-
 86 tire pre-burn combustion, cooling, and spray combustion phase. The output
 87 voltage from the charge amplifier was acquired at a frequency of 100 kHz by
 88 a DAQ card (National InstrumentTM PCI 6040E).

89 The fuel injection system consists of a ten-hole solenoid-operated gasoline
 90 multi-hole injector and a compressed air-driven liquid pump. The injector
 91 used in this study is a Bosch custom made high-pressure injector (HDEV5s)
 92 provided by Saudi Aramco for research purposes. The injector hole size is
 93 $165\ \mu m$ with a cone angle of 110° . This injector was designed for work-
 94 ing at high injection pressures of up to 500 bar. A compressed air-driven
 95 liquid pump (Hydraulic International, Inc. 5LSD-410) is used to pressur-
 96 ize the fuel to a maximum pressure of up to 3000 bar. A common rail is
 97 connected with the pump and controlled by a LabVIEWTMPID program to
 98 stabilize the fuel injection pressure. The solenoid injector is controlled us-
 99 ing a direct injection driver system (National InstrumentsTMDIDS-2003). A
 100 dynamic pressure sensor (Kistler 4067E) was fitted to the high-pressure pipe

101 connecting the common rail and the injector at 70mm from the injector end
 102 similar to the ECN community [29]. The dynamic pressure sensor can mea-
 103 sure pressure range between 0-3000bar under a working temperature range
 104 of 25-180° C. The high-pressure pipes used are rated at 4000bar.

Figure 1: Schematic of pre-burn type Constant Volume Combustion Cham-
 ber (CVCC): 1. Delay generator; 2. Data acquisition; 3. PC Software; 4.
 High speed camera; 5. Fuel tank; 6. Common rail; 7. Air driven liquid
 pump; 8. CVCC; 9. Gas pressure sensor; 10. Gas accumulator; 11. Gas
 cylinders.

105 A high-speed monochrome camera (Photron SA-X2) was used to visualize
 106 the combustion event. The camera was employed at 50 kfps to capture the
 107 flame evolution with a resolution of 496×384 pixels. Camera exposure time
 108 and the aperture number were selected based on the flame intensity under
 109 different ambient conditions. The camera triggering event was synchronized

110 with the fuel injection event through a digital pulse generator (Stanford re-
111 search systems DG535).

112 **3. Test conditions**

113 Ignition delay time measurements have been performed at different exper-
114 imental conditions, which are summarized in table 2. Three different injection
115 pressures of 100, 300, and 450 bar were tested. For each injection pressure,
116 two different ambient pressures (20 and 30 bar), three different ambient tem-
117 peratures (800, 900, and 1000K), and three different oxygen concentrations
118 (10, 15, 21%) were used. An injection duration of 1.75 ms has been used
119 to ensure fully developed spray. The injection rate measurements were per-
120 formed using a spray momentum flux method. Details of the measurement
121 principle can be found in [30]. Fig. 2 shows the injection rate profile for
122 three different injection pressures used in this study. The total mass of fuel
123 injected at 100, 300, and 450 bar injection pressures was 25, 42.5, and 50
124 mg, respectively. The experiments were repeated three times for each case.
125 Then the data from the three runs were averaged and reported to account
126 for the uncertainties.

127 **4. Definition**

128 The ignition delay time was quantified from the heat release rates cal-
129 culated based on the pressure measurements during the spray combustion
130 events, as shown in Fig. 3.

Figure 2: Injection rate profiles along with injector current profile for different injection pressures used

Figure 3: Ignition delay quantification from pressure measurement data
a) Raw and fitted pressure data b) Heat release rate c) Accumulated heat release

Table 2: Test conditions

Ambient pressure (bar)	20 and 30
Ambient temperature (K)	800, 900, and 1000
Injection pressure (bar)	100, 300, and 450
Oxygen concentration (%)	10, 15, 21

132 decay curve by subtracting an exponentially fitted pressure curve from the
133 original signal. Then the heat release rate is calculated by the formula given
134 in Eq. 1.

$$\frac{dQ}{dt} = \frac{1}{\gamma - 1} V \frac{dP}{dt} \quad (1)$$

135 where Q is the heat release in Joule (J), t is the time in second (s), V is
136 the volume in (m^3), P is the pressure in Pascal (Pa), and γ is the ratio of
137 the specific heats and in this study γ value was taken to be 1.4.

138 The accumulated heat release is obtained by numerical integration of the
139 heat release rate. In this study, the ignition delay obtained from pressure
140 measurement is defined as the time after start of excitation (ASOE) of the
141 injector until 1% of the accumulated heat release has occurred [31].

142 5. Results and discussion

143 Fig. 4 shows the ignition delay time at different a) injection pressure,
144 b) ambient temperature, c) ambient pressure, and d) oxygen concentrations.
145 The ignition delay time spanned from $75 \mu s$ to 4.5 ms. In some cases, the

146 reported ignition delay times occur later than the hydraulic end of injection
 147 tion (2.78, 2.64, and 2.57 ms for 100, 300, and 450 bar injection pressures
 148 respectively) (refer Fig. 2). This shows that the combustion ranges from
 149 conventional diffusion combustion to partially premixed combustion mode.

Figure 4: Ignition delay times for GCI RON 77 fuel at different a) ambient pressures, b) ambient temperatures, c) oxygen concentrations and d) injection pressures

150 It can be seen from Fig. 4a, the ignition delay shows an inverse dependence
 151 on the ambient pressure similar to the ignition delay times reported

152 from shock tube and rapid compression machines [13]. It can be noted that
153 the ignition delay at ambient pressure of 30 bar and injection pressures of 300
154 and 450 bar is 2.813 ms; this shows that the combustion starts immediately
155 after the end of injection (2.64 and 2.57 ms). For lower injection pressure
156 of 100 bar at ambient pressure of 30 bar and all injection pressures at am-
157 bient pressure of 20 bar, the ignition delay is longer than 3.5 ms, which is
158 later than their respective end of injections. Therefore, partially-premixed
159 combustion is expected, and the mixture stratification is dependent on the
160 ambient pressures.

161 The ignition delay dependence on ambient temperature is shown in Fig.
162 4b. The ignition delay at 800, 900, and 1000K at ambient pressure of 30 bar,
163 the oxygen concentration of 10%, and an injection pressure of 100 bar are
164 reported as 3.526, 2.626, and 1.82 ms respectively. The end of injection for
165 100 bar injection pressure is 2.78 ms. This shows that as the ambient tem-
166 perature is reduced, the combustion mode transits from spray diffusion to
167 partially-premixed combustion. Fig. 5 shows the heat release rate and accu-
168 mulated heat release for the different ambient temperatures of 800, 900, and
169 1000 K at ambient pressure of 30 bar and oxygen concentration of 10% for
170 injection pressure of 100 bar. As the ambient temperature is decreased, the
171 accumulated heat release increases. This shows that the partially-premixed
172 combustion mode is more efficient than the spray diffusion mode of com-
173 bustion. A comparison of auto-ignition flame images is shown in Fig. 6 at
174 different ambient temperatures under ambient pressure of 30 bar, an injection
175 pressure of 100 bar, and oxygen concentration of 10%. It can be seen from
176 the images that at ambient temperatures of 1000 K and 900 K, combustion is

Figure 5: Comparison of heat release rate and accumulated heat release for two different auto-ignition images of GCI RON 77 fuel at different ambient temperatures under ambient pressure of 30 bar, the injection pressure of 100 bar and Oxygen concentration of 10%

177 predominantly characterized by high-intensity luminous flames due to spray
 178 diffusion combustion mode, and at 800 K it is described by low-temperature
 179 partially-premixed combustion. Further, high luminosity flames with higher
 180 soot formation results in more heat loss due to thermal radiation, which con-
 181 tributes to the lower accumulated heat release at the end of combustion as
 182 seen in Fig.5 for ambient temperatures of 900 K and 1000 K compared to
 183 that of 800 K.

Figure 6: Comparison of auto-ignition images of GCI RON 77 fuel at different ambient temperatures under ambient pressure of 30 bar, the injection pressure of 100 bar and Oxygen concentration of 10%.

184 Fig. 4c shows that ignition delay for different oxygen concentrations at
185 ambient temperatures of 800 and 1000K, the ambient pressure of 30 bar,
186 and an injection pressure of 450 bar. It can be seen that the ignition delay
187 decreases as the ambient oxygen concentration increases. It should be noted
188 that for higher injection pressure of 450 bar, the combustion is predominantly
189 governed by spray diffusion since the ignition delay is mostly earlier than the
190 end of injections. The level of spray diffusion combustion mode increases as
191 the oxygen concentration increases. A comparison of flame images is shown
192 in Fig. 7 for different oxygen concentrations at ambient pressure of 30 bar,
193 the ambient temperature of 1000 k, and an injection pressure of 450 bar.

194 Fig. 4d shows the ignition delay dependence on the injection pressure.
195 The ignition delays are reported for different injection pressures at ambient
196 pressure of 30 bar, ambient temperature of 1000 K, and oxygen concentration
197 of 15%. It is seen that the ignition delay changes very little with the increase
198 in injection pressure, and it is interesting to note that the ignition delay for
199 injection pressures of 300 and 450 bar is almost the same. This behavior
200 shows that the chemical delay compensates for the difference in the physical
201 delay due to variation in the local equivalence ratio. Fig. 8 shows the flame
202 images comparison for different injection pressures under an ambient tem-
203 perature of 1000K, the ambient pressure of 30 bar, and oxygen concentration
204 of 15%. It can be seen that the combustion is predominantly dominated
205 by spray diffusion mode from high-intensity luminous flame images as the
206 ignition starts well before the end of injection.

Figure 7: Comparison of auto-ignition images of GCI RON 77 fuel at different Oxygen concentrations under ambient pressure of 30 bar, ambient temperature of 1000 K and injection pressure of 450 bar.

Figure 8: Comparison of auto-ignition images of GCI RON 77 fuel at different injection pressures under ambient pressure of 30 bar, ambient temperature of 1000 K and Oxygen concentration of 15%.

207 6. Conclusions

208 This work investigates the auto-ignition of sprays of high-reactivity gaso-
 209 line fuel (GCI RON 77) using a multi-hole high-pressure gasoline injector
 210 under different operating conditions. Different combustion modes were ob-
 211 served.

- 212 • It was found that the auto-ignition was observed with noticeable igni-

213 tion delay under all conditions tested.

- 214 • At high injection pressure of 450 bar and high ambient gas pressure
215 of 30 bar irrespective of oxygen concentration and ambient gas tem-
216 perature, the ignition delays are shorter and exhibits diffusion mode of
217 combustion.
- 218 • Further, at a high ambient gas temperature of 1000 K and high am-
219 bient gas pressure of 30 bar, irrespective of oxygen concentration and
220 injection pressure, the ignition delays are short and exhibits diffusion
221 combustion
- 222 • At very relevant GCI engine operating conditions of a low ambient
223 gas temperature of 800 K and low oxygen percentage of 10% (high
224 EGR scenario), irrespective of other parameters, the ignition delays
225 are longer and exhibits partially-premixed combustion mode.

226 **7. Acknowledgments**

227 This work was sponsored by Saudi Aramco under the FUELCOM II pro-
228 gram and by King Abdullah University of Science and Technology.

229 **References**

- 230 [1] Y. Zhang, P. Kumar, M. Traver, D. Cleary, Conventional and low tem-
231 perature combustion using naphtha fuels in a multi-cylinder heavy-duty
232 diesel engine, SAE Int J Engines 9 (2016) 1021–1035.

- 233 [2] J. Chang, Y. Viollet, A. Amer, G. Kalghatgi, Fuel economy potential of
234 partially premixed compression ignition (PPCI) combustion with naph-
235 tha fuel, Technical Report, SAE Tech Pap 2013-01-2701, 2013.
- 236 [3] G. Kalghatgi, L. Hildingsson, A. Harrison, B. Johansson, Autoignition
237 quality of gasoline fuels in partially premixed combustion in diesel en-
238 gines, *Proc Combust Inst* 33 (2011) 3015 – 3021.
- 239 [4] M. Sellnau, M. Foster, K. Hoyer, W. Moore, J. Sinnamon, H. Husted,
240 Development of a gasoline direct injection compression ignition (gdc) engine,
241 *SAE Int J Engines* 7 (2014) 835–851.
- 242 [5] A. M. Ickes, S. V. Bohac, D. N. Assanis, Effect of fuel cetane number
243 on a premixed diesel combustion mode, *Int J Engine Res* 10 (2009)
244 251–263.
- 245 [6] D. Han, A. M. Ickes, S. V. Bohac, Z. Huang, D. N. Assanis, Premixed
246 low-temperature combustion of blends of diesel and gasoline in a high
247 speed compression ignition engine, *Proc Combust Inst* 33 (2011) 3039
248 – 3046.
- 249 [7] G. T. Kalghatgi, L. Hildingsson, A. J. Harrison, B. Johansson, Surrogate
250 fuels for premixed combustion in compression ignition engines, *Int J*
251 *Engine Res* 12 (2011) 452–465.
- 252 [8] J. Badra, Y. Viollet, A. Elwardany, H. G. Im, J. Chang, Physical and
253 chemical effects of low octane gasoline fuels on compression ignition
254 combustion, *Appl Energy* 183 (2016) 1197 – 1208.

- 255 [9] J. Chang, G. Kalghatgi, A. Amer, P. Adomeit, H. Rohs, B. Heuser,
256 Vehicle demonstration of naphtha fuel achieving both high efficiency
257 and drivability with euro6 engine-out nox emission, SAE Int J Engines
258 6 (2013) 101–119.
- 259 [10] Y. Zhang, A. Voice, T. Tzanetakis, M. Traver, D. Cleary, An evaluation
260 of combustion and emissions performance with low cetane naphtha fuels
261 in a multicylinder heavy-duty diesel engine, J Eng Gas Turb Power 138
262 (2016) 102805.
- 263 [11] C. P. Kolodziej, M. Sellnau, K. Cho, D. Cleary, Operation of a gasoline
264 direct injection compression ignition engine on naphtha and e10 gasoline
265 fuels, SAE Int J Engines 9 (2016) 979–1001.
- 266 [12] C. Jiang, G. Huang, G. Liu, Y. Qian, X. Lu, Optimizing gasoline com-
267 pression ignition engine performance and emissions: Combined effects
268 of exhaust gas recirculation and fuel octane number, Appl Therm Eng
269 153 (2019) 669–677.
- 270 [13] M. AlAbbad, J. Badra, K. Djebbi, A. Farooq, Ignition delay measure-
271 ments of a low-octane gasoline blend, designed for gasoline compression
272 ignition (gci) engines, Proc Combust Inst (2018).
- 273 [14] B. Mohan, W. Yang, S. Kiang Chou, Fuel injection strategies for per-
274 formance improvement and emissions reduction in compression ignition
275 engines—a review, Renew Sust Energ Rev 28 (2013) 664 – 676.
- 276 [15] R. Vallinayagam, S. Vedharaj, Y. An, A. Dawood, M. I. Najafabadi,
277 B. Somers, B. Johansson, Combustion stratification for naphtha from

- 278 CI combustion to PPC, Technical Report, SAE Tech Pap 2017-01-0745,
279 2017.
- 280 [16] H. Goyal, S. Kook, Ignition process of gasoline compression ignition
281 (gci) combustion in a small-bore optical engine, *Fuel* 256 (2019) 115844.
- 282 [17] L. Wang, Z. Wu, A. Ahmed, J. A. Badra, S. M. Sarathy, W. L. Roberts,
283 T. Fang, Auto-ignition of direct injection spray of light naphtha, primary
284 reference fuels, gasoline and gasoline surrogate, *Energy* 170 (2019) 375–
285 390.
- 286 [18] J. Du, B. Mohan, J. Sim, T. Fang, W. L. Roberts, Macroscopic non-
287 reacting spray characterization of gasoline compression ignition fuels in
288 a constant volume chamber, *Fuel* 255 (2019) 115818.
- 289 [19] J. Du, B. Mohan, J. Sim, T. Fang, W. L. Roberts, Experimental and
290 analytical study on liquid and vapor penetration of high-reactivity gaso-
291 line using a high-pressure gasoline multi-hole injector, *Appl Therm Eng*
292 163 (2019) 114187.
- 293 [20] R. Novella, A. García, J. Pastor, V. Domenech, The role of detailed
294 chemical kinetics on cfd diesel spray ignition and combustion modelling,
295 *Math Comp Model Dyn* 54 (2011) 1706 – 1719.
- 296 [21] P. Sementa, B. M. Vaglieco, F. Catapano, Thermodynamic and optical
297 characterizations of a high performance gdi engine operating in homoge-
298 neous and stratified charge mixture conditions fueled with gasoline and
299 bio-ethanol, *Fuel* 96 (2012) 204–219.

- 300 [22] P. Sementa, B. M. Vaglieco, F. Catapano, Non-intrusive investigation
301 in a small gdi optical engine fuelled with gasoline and ethanol, SAE Int
302 J Engines 4 (2011) 50–66.
- 303 [23] B. G. Moxey, A. Cairns, H. Zhao, A comparison of butanol and ethanol
304 flame development in an optical spark ignition engine, Fuel 170 (2016)
305 27–38.
- 306 [24] H. Zhao, N. Ladommatos, Optical diagnostics for soot and temperature
307 measurement in diesel engines, Prog Energ Combust 24 (1998) 221–255.
- 308 [25] T. Xuan, J. V. Pastor, J. M. García-Oliver, A. García, Z. He,
309 Q. Wang, M. Reyes, In-flame soot quantification of diesel sprays un-
310 der sooting/non-sooting critical conditions in an optical engine, Appl
311 Therm Eng 149 (2019) 1–10.
- 312 [26] Y. An, R. Vallinayagam, S. Vedharaj, J.-B. Masurier, A. Dawood, M. I.
313 Najafabadi, B. Somers, B. Johansson, Analysis of transition from HCCI
314 to CI via PPC with low octane gasoline fuels using optical diagnostics
315 and soot particle analysis, Technical Report, SAE Tech Pap 2017-01-
316 2403, 2017.
- 317 [27] H. Shi, Y. An, B. Johansson, Study of Fuel Octane Sensitivity Effects
318 on Gasoline Partially Premixed Combustion Using Optical Diagnostics,
319 Technical Report, SAE Tech Pap 2019-24-0025, 2019.
- 320 [28] R. S. Baert, P. J. Frijters, B. Somers, C. C. Luijten, W. de Boer, Design
321 and operation of a high pressure, high temperature cell for HD diesel

- 322 spray diagnostics: guidelines and results, Technical Report, SAE Tech
323 Pap 2009-01-0649, 2009.
- 324 [29] L. M. Pickett, C. L. Genzale, G. Bruneaux, L.-M. Malbec, L. Hermant,
325 C. Christiansen, J. Schramm, Comparison of diesel spray combustion in
326 different high-temperature, high-pressure facilities, SAE Int J Engines
327 3 (2010) 156–181.
- 328 [30] B. Mohan, J. Du, J. Sim, W. L. Roberts, Hydraulic characterization of
329 high-pressure gasoline multi-hole injector, Flow Meas Instrum 64 (2018)
330 133–141.
- 331 [31] M. Tang, J. Zhang, T. Menucci, H. Schmidt, S. Lee, J. Naber, T. Tzane-
332 takis, Experimental spray ignition and soot forming characteristics of
333 high reactivity gasoline and diesel fuel in a heavy-duty single-hole in-
334 jector, in: Proceedings 10th US National Combustion Meeting–Eastern
335 States Section of the Combustion Institute, College Park, MD, 2017.