Early Injection for Low Emissions

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Low-emission and high-efficiency have always been the targets for Internal Combustion Engine development. For diesel engines, homogeneous charge (aka. HCCI) and premixed charge (aka. PCCI) combustion modes provide both low-emission and high-efficiency simultaneously. To achieve these advanced combustion modes, early injection is needed as a relatively longer air-fuel mixing time is guaranteed. Several key parameters, such as the injection timing, pressure, angle, directly determine the final combustion process and thus the emission and efficiency performance. The pros and cons of these key parameters are discussed in detail here to provide a good review of the early-injection strategy.

Keywords: early injection ; HCCI ; PCCI ; Internal Combustion Engine ; Diesel Engine ; NOx ; Soot

1. Advanced Combustion Modes: HCCI and PCCI

The conventional diesel combustion process can be classified into four major phases: ignition delay, premixed combustion, mixing controlled combustion, and the late burning phase[1]. The conventional combustion phase regime encompasses both NOx and soot islands, as shown in Figure 1. This is not preferable while considering the more and more stringent emission regulations. Therefore, advanced combustion modes that could eliminate or avoid the fuel-rich and high-temperature environment are needed.

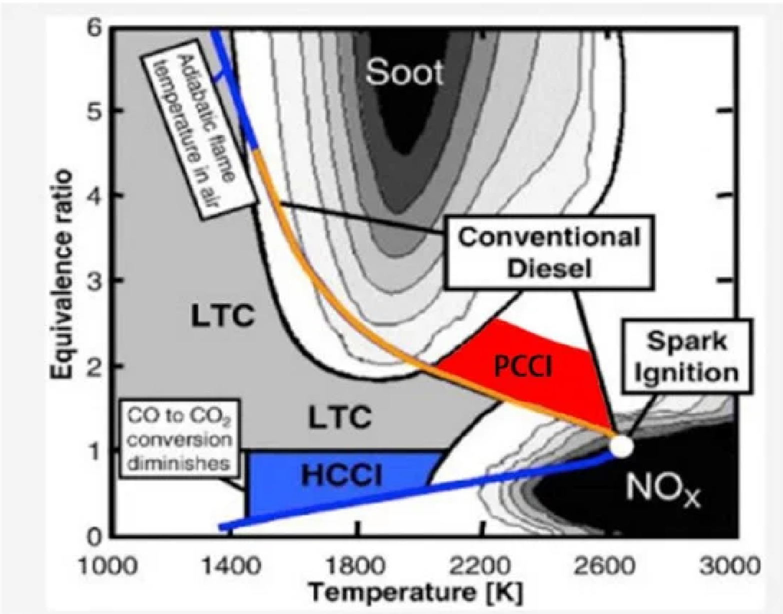

Figure 1. φ-T diagram of conventional combustion, homogeneous charge compression ignition (HCCI) combustion, and premixed charge compression ignition (PCCI) combustion[2]. φ, equivalence ratio; T, temperature.

HCCI combustion was first proposed by Onishi et al.[3] and Noguchi et al.[4]. The main characteristic of HCCI is a (more or less homogeneous) premixed air-fuel mixture that undergoes auto-ignition as a result of compression. A major difficulty in HCCI is to get a homogeneous admixture of air and fuel. Besides, the high cetane number of conventional diesel fuel results in large rates of pressure rise and difficulties in combustion phasing control[5][6][7][8][9].

PCCI combustion has been described as a middle path between conventional and HCCI combustion modes[10][11][12][13]. For PCCI combustion, only part of the fuel undergoes the HCCI type of clean combustion, while the remainder undergoes conventional combustion. Table 1shows that both HCCI and PCCI provide clear advantages out of the conventional diesel combustion mode regarding the soot and NOx emissions.

Table 1. Comparison of key characteristics of conventional diesel, HCCI, and PCCI combustion.

	Conventional Combustion	HCCI Combustion	PCCI Combustion
Injection strategy	injection close to Top Dead Center (TDC)	Early injection	Early injection + TDC injection
Combustion mode	Diffusion	Premixed	Premixed + diffusion
Ignition	Auto-ignition (controlled by injection timing)	Auto-ignition (controlled by chemical kinetics)	Auto-ignition (controlled by injection timing)
Combustion temperature	Partially high	Relatively low	Relatively low
NOx	High NOx emissions due to high combustion temperature	Low NOx emissions due to low combustion temperature	Low NOx emissions due to low temperature and exhaust gas recycling (EGR) dilution
Soot	High soot emissions due to diffusion combustion mode	Low soot emissions due to lean homogeneous charge	Low soot emissions due to lean homogeneous charge

2. Early Injection Strategy Definition

In order to allow enough time for fuel to mix with the air before combustion, the early injection strategy, by which the fuel is injected in an early stage of the compression stroke, has been applied widely in HCCI and PCCI diesel engines. The start of early injection is typically 20–200 before the top dead center(BTDC). Based on the characteristic of HCCI and PCCI combustion, the early injection strategy can be classified as a single injection and two-stage injection, as seen in Figure 2. For a two-stage injection, the first injection is also called the pilot injection, and the second injection is also called the main injection. Based on the injection timing, the early injection strategy can be divided into three patterns, as seen in Figure 3: The injection closest to TDC is defined as late; that farthest from TDC is defined as early, and the one in between is defined as middle[14]. The demarcation points of these three patterns in this paper are defined as 60, 40, and 20 BTDC, respectively.

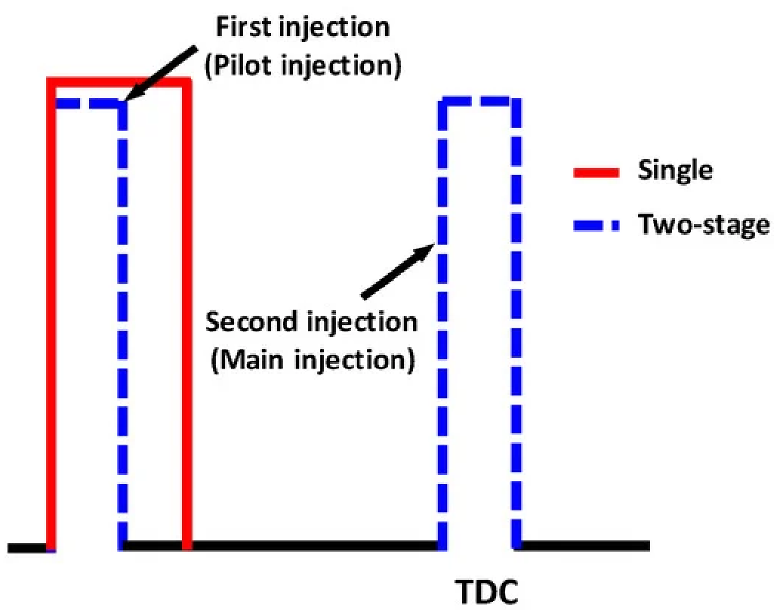

Figure 2. Single and two-stage early injection strategy.

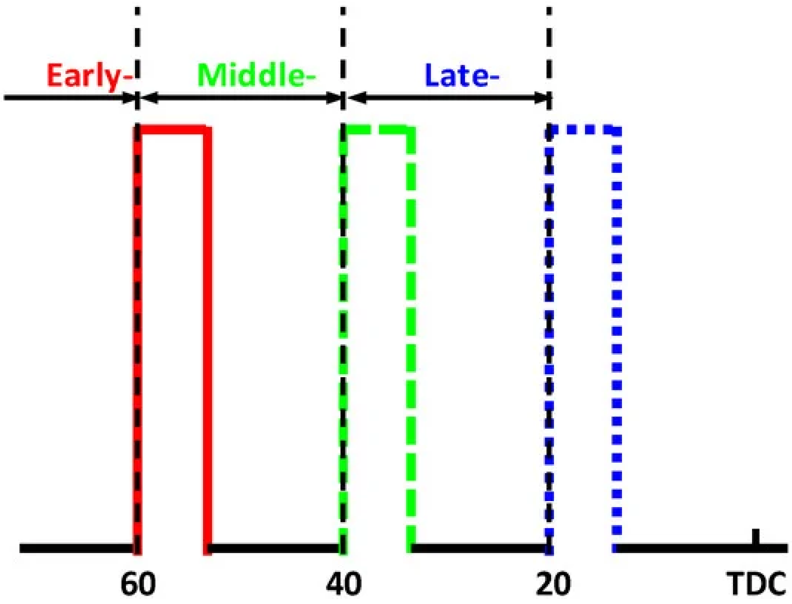

Figure 3. Early injection strategy divided by injection timing.

Using the early injection strategy will cause a wall-wetting problem and leads to (1) low combustion eciency, (2) excessive soot/carbon monoxide (CO)/hydrocarbon (HC) emissions, and (3) (local) oil dilution[15][16]. Many methods, including limiting the injection angle, have been proposed to limit or reduce wall-wetting.

Overall, there are several key parameters in the early-injection process that define the final combustion and emission performances. The effects of fuel injection pressure, injection timing, and injection angle on engine performance and emissions are discussed in detail separately in the following sections.

3. Effects of Injection Pressure

Injection pressure could change the combustion and the emissions significantly as it directly determines the fuel spray, injection duration, and therefore the time to mix air and fuel into a homogenous mixture. However, it is not a straightforward approach to have lower emissions by simply increasing the injection pressure. Table 2 below gives details about the emissions along with changing the injection pressure.

Table 2. Variation of performance and emissions after increasing the injection pressure. BSFC, brake-specific fuel consumption.

Author	Injection Pressure (bar)	Fuel	BSFC	NOx	HC	CO	Soot
Jeong et al.[17]	500–900	Diesel	na	→	na	na	↓
Fang et al.[18]	600/1000	Diesel	na	↑	na	na	↓
Shimazaki et al.[19]	300–1200	Diesel	↓↑	↓	↑	↑	→
Kiplimo et al.[20]	800/1400	Diesel	↓	↑	↓	→	↓
Liu et al.[21]	600–1400	Diesel	na	na	na	na	→

Chen et al. [22]	1000–1400	Diesel	↓	↑	na	na	↓
Siewert[23]	800–1600	Diesel	↓	na	↓	↓	↓
Park et al. [24]	400/1200	Bioethanol blends	↓	↑	↑	↑	↓
Arun et al. [25]	200–240	Carbon black–water–diesel	na	↓↑	↓↑	↓↑	↓↑
Nanthagopal et al.[26]	200–240	Biodiesel	↓	↑	↓	↓	↓

4. Effects of Injection Timing

On one hand, injecting the fuel at an earlier time prolongs the ignition delay and helps to create a more homogeneous mixture. The formed lean mixture is then burned at a low temperature, resulting in low NOx emissions. On the other hand, the cylinder pressure and temperature are low under earlier injection timing, which leads to poor fuel evaporation and the wall-wetting problem.

4.1 Single Early Injection Timing Effects

Table 3 shows a summary of the variation of performance and emissions of the HCCI engine after advancing the early injection timing. In general, advancing the injection timing results in better NOx emissions but worse HC and CO emissions. However, the final soot emission depends on the opposite effects mentioned above. Engine performance deteriorates with advanced injection timing due to the increased negative work and incomplete combustion.

Table 3. Variation of performance and emissions after advancing the early injection timing (single).

Author	Injection Timing (° BTDC)	Fuel	BSFC	NOx	HC	CO	Soot
Benajes et al.[27]	33–24	Diesel	na	na	↑	↑	↑
Kiplimo et al.[20]	40–20	Diesel	↑	↓	↑	↑	↑
Kim and Lee[28]	70–20	Diesel	↑	↓	na	na	na
Fang et al. [30]	80–40	Diesel	na	↓	na	na	↑
Kim et al. [31]	180–20	Diesel	↑	na	na	na	↓

Kim et al. [32]	180–20	Diesel	↑	↓	na	na	↓
Miyamoto et al.[33]	180–20	Diesel	na	↓	↑	na	↓
Kook et al. [29]	200–50	Diesel	↑	↓	↑	↑	↓
Park et al. [24]	40–20	Bioethanol blends	↑	↓	↑	↑	↑
Yoon et al. [34]	40–20	DME	↑	↓	↑	↑	→
Kim et al. [35]	40–20	Gasoline	↑	↓	↑	↑	na
Wamankar and Murugan[36]	26–20	Diesel	↑	↓	↑	↑	↑

4.2 Two-stage Early Injection

In PCCI combustion, a two-stage early injection strategy is utilized. In general, advancing the first injection timing will decrease NOx and soot emissions and increase HC and CO emissions. Engine performance deteriorates with advanced injection timing due to the increased negative work and incomplete combustion. The second injection is considered to act as the ignition controller and promoter of PCCI combustion. The second injection timing mainly influences the second stage of the combustion process, which is mainly diffusive combustion. With retarded second injection timing, the major combustion event was delayed. The variation of BSFC of different second injection timings mainly depended on whether the combustion event shifted to near TDC. In addition, NOx emissions decreased when the second injection timing was retarded because of the low charge temperature caused by the late combustion. Soot emissions generally increased as the second injection was retarded. This was because of the increased portion of diffusion combustion and low charge temperature. HC and CO emissions also increased with retarded second injection timing.

5. Effects of Injection Angle

Wall-wetting caused by the early injection strategy directly influenced the performance and emissions of the HCCI diesel engine. Limiting the injection angle has been proved to be a useful approach to reduce the wall-wetting phenomenon. The magnitude and direction of the spray rotation in the bowl were directly affected by the injection angle, as shown in Figure 4. This difference further impacted the fuel-air mixing in the piston bowl and finally impacted combustion and emissions. As mentioned above, the impingement target is an important factor influencing emissions and is commonly determined by the injection timing, injection angle, and piston structure.

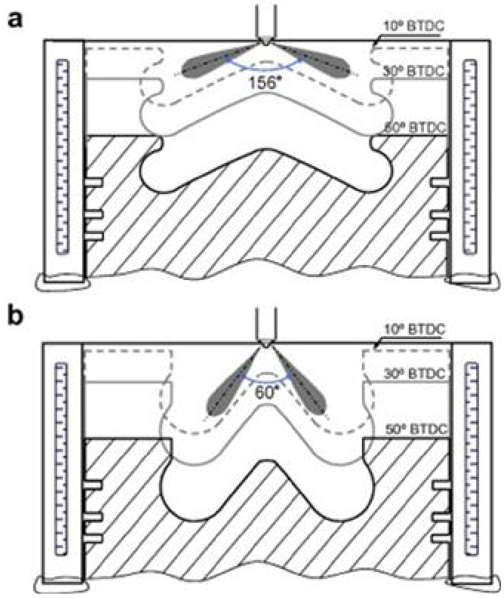

Figure 4. Schematic diagrams of the tested combustion chamber and fuel spray: (a) conventional diesel engine; (b) modified engine configuration for early injection [28].

Table 4 shows a summary of the variation of performance and emissions of HCCI and PCCI engines after decreasing the injection angle. In general, decreasing the injection angle will limit or reduce the wall-wetting phenomenon, resulting in decreased HC and CO. However, soot emission is directly affected by the placement of spray targeting. Decreasing the injection angle generally is not good for the control of soot emission, but NOx emission can be suppressed by the rich fuel-air mixture and low combustion temperature.

Table 4. Variation of performance and emissions after decreasing the injection angle (two-stage).

Author	**Injection Angle (°)**	**Fuel**	**BSFC**	**NOx**	**HC**	**CO**	**Soot**
Kim and Lee[28]	60/156	Diesel	↓	→	na	na	na
Fang et al.[18]	70/150	Diesel	na	↓	na	na	↑
Kim et al. [31]	70–150	Diesel	↓	na	na	na	↑
Mobasheri and Peng	90–145	Diesel	↓↑	↓	na	na	↓↑
Vanegas et al.[37]	100–148	Diesel	na	↑	na	na	↑
Kook and Bae	100/150	Diesel	na	↑	↓	↓	↓
Siewert[23]	100–158	Diesel	na	na	↓	↓	↓
Park et al. [38]	70/156	Bioethanol blended	↓	na	↓	↓	na

Yoon et al.[34]	60/70/156	DME	↓	→	↓	↓	→

6. Combination of Early-Injection and Alternative Fuels

Changing the fuel properties and using alternative fuel are also promising ways to improve the combustion and emissions of HCCI and PCCI engines[39][40][41]. Biodiesel fuel, as one alternative diesel fuel, is currently of great interest and an important research subject. Biodiesel fuels contain oxygen and thus provide an effective way to eliminate the over-rich regions and enhance the combustion process, resulting in low soot, HC, and CO emissions[42][43][44][45]. Dimethyl ether (DME) is another alternative fuel. Its good ignition capability and high latent heat lead to decreased cylinder temperature in the combustion phase[46][47]. Besides, the oxygenated molecular structure and good atomization properties help in the formation of a leaner and more homogeneous mixture. The alternative fuels bioethanol and n-butanol are also widely used due to their high oxygen concentration[48][49][50][51][52].

As HCCI combustion is mainly controlled by chemical kinetics, the combustion process and burning rate are dependent on fuel properties. Studies have shown that optimal physicochemical properties are needed under different operating conditions; e.g., fuel with a high cetane number is required for light loads and high-octane fuel for heavy loads[53][54][55][56]. Gasoline/diesel dual-fuel combustion was proved to be a useful approach to control the combustion phasing and heat release rate of HCCI by adjusting the blending ratio according to different operating conditions[57][58].

7. Summary and Conclusions

Several key parameters in early injection strategy were covered and discussed here mainly focus on engine combustion and emission performances. Both experimental and numerical works had been conducted widely, and the advantages and disadvantages, in terms of the engine emissions, of early injection strategy are listed in Table 5.

Table 5. Advantages and disadvantages of early injection parameters.

Early Injection Parameters	Injection Pressure ↑	Injection Timing				Injection Angle ↓
		Single ←	Two-Stage			
			First Injection Timing ←	Second Injection Timing →	First Injection Quality ↑	
Advantage	Better air–fuel mixing and fewer fuel-rich regions. Higher heat release rate and temperature. Shorter combustion duration. Higher engine thermal efficiency. Better oxidation of soot, CO, and HC emissions.	Longer premixing time. Better air–fuel mixing and more homogeneous mixture. Lower NOx and soot emissions.	Same as advancing single early injection timing. Second combustion stage promoted soot oxidation.	Lower combustion temperature. Lower NOx emissions.	Better air–fuel mixing and more homogeneous mixture for first combustion stage. Lower NOx and soot emissions.	Decreased wall-wetting fuel. Better air–fuel mixing and more homogeneous mixture. Lower soot, CO, and HC emissions.
Disadvantage	Longer spray penetration. More serious wall-wetting results in more soot, CO, and HC emissions. Higher combustion temperature results in higher NOx emissions.	Lower cylinder pressure and temperature during injection period. More serious wall-wetting. Shifting combustion event to earlier side results in more negative work. Deteriorated combustion efficiency and increased incomplete combustion products. Higher soot, CO, and HC emissions.	Same as advancing single early injection timing.	Increased diffusive combustion portion. Higher soot, CO, and HC emissions.	Advancing ignition results in more negative work. Shorter ignition delay and higher combustion temperature of second combustion stage results in higher NOx emission. More serious wall-wetting Higher soot, CO, and HC emissions.	Impingement between spray and piston bowl especially for second injection. Increasing fuel deposition on piston bowl results in higher soot, CO, and HC emissions.

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