Early Injection Strategy for Low-emission Premixed-Combustion Engine

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Definition

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.

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\(^1\). During the premixed combustion phase, polyaromatic hydrocarbons, the precursors of soot, are quickly formed in the hot (1600–2000 K), fuel-rich combustion regions. Soot formation follows, filling the entire downstream jet cross-section. Near the peak heat release rate of premixed combustion, a diffusion flame forms in the periphery of the fuel-rich, high-temperature downstream regions of the jet. NOx emission forms in the hot (1800–2000 K) and near-stoichiometric mixtures in the periphery of the jet near the diffusion flame. So 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.](image-url)
HCCI combustion was first proposed by Onishi et al. and Noguchi et al. The main characteristic of HCCI is a (more or less homogeneous) premixed air-fuel mixture that undergoes auto-ignition as a result of compression. The auto-ignition allows the combustion of a very lean mixture, which helps to eliminate the fuel-rich region, resulting in low soot emission. The combustion temperature is significantly lower than that of conventional diesel combustion, which is beneficial for the reduction of NOx emissions. However, a major difficulty in HCCI is to get a homogeneous admixture of air and fuel. This is especially true for diesel engines, because the lower volatility of diesel fuels makes it more difficult to obtain a homogeneous mixture compared to gasoline fuels. Besides, the high cetane number of conventional diesel fuel results in large rates of pressure rise and difficulties in combustion phasing control.

PCCI combustion has been described as a middle path between conventional and HCCI combustion modes. In HCCI combustion, there is the challenge of combustion phasing control and homogeneous mixture preparation. To overcome these problems, for PCCI combustion, only part of the fuel undergoes the HCCI type of clean combustion, while the remainder undergoes conventional combustion. Since the remaining fuel undergoes conventional combustion, the combustion phasing is still controlled by the injection timing. Also, only partial fuel is used to prepare the homogeneous mixture, so the mixture preparation for PCCI combustion is simpler than for HCCI combustion. The part of the premixed fuel results in peak equivalence ratios staying below the soot formation threshold. Further, high levels of EGR are often used to decrease the oxygen concentration and lower peak flame temperatures, resulting in the movement of the NOx island.

As given by Table 1, 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.

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

2. Early Injection Strategy Definition

The preparation of a homogeneous mixture is important for both HCCI and PCCI combustion. 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\(^1\). The demarcation points of these three patterns in this paper are defined as 60, 40, and 20 BTDC, respectively.

![Figure 3. Early injection strategy divided by injection timing.](image)

Most of these early injection strategies have a certain unavoidable influence on the fuel spray formation inside the combustion chamber, further affecting the combustion and emissions of HCCI and PCCI engines. In addition, using the early injection strategy will cause a wall-wetting problem. Because of the lower temperature of the gas and the density in the cylinder during the early injection period, the fuel spray will impinge on the cylinder wall or piston head due to the slow fuel vaporization rate and longer liquid penetration length. Wall-wetting mainly leads to (1) low combustion efficiency, (2) excessive soot/carbon monoxide (CO)/hydrocarbon (HC) emissions, and (3) (local) oil dilution\(^1\). 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.

On the one hand, higher injection pressure results in shorter injection duration and longer premixing time before the onset of combustion. The increased injection pressure leads to better atomization of the fuel, which causes better air-fuel mixing and fewer fuel-rich regions. This results in a higher heat release peak, with a rapid burn rate and a shorter combustion duration, which is beneficial for engine thermal efficiency. In addition, the in-cylinder temperature for higher injection pressure is higher than that for low injection pressure. The better air-fuel mixing and higher in-cylinder temperature benefit the oxidation of soot, CO, and HC.

On the other hand, the length of spray penetration increases under higher injection pressure. This can cause serious spray-wall impingement, because both the in-cylinder temperature and pressure are low for the early injection duration. Fuel impingement on the piston head or cylinder wall leads to incomplete fuel vaporization and oxidation, which creates either over-rich or over-lean regions. This conflicts with the advantage of atomization with higher injection pressure mentioned above.

Similarly, the final NOx emission is also a result of these paradoxical effects. High in-cylinder temperature is usually observed with high fuel injection pressure, which promotes the formation of NOx. However, a better mixing process under high injection pressure makes it easier to achieve HCCI combustion, which brings low NOx emission.

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

<table>
<thead>
<tr>
<th>Author</th>
<th>Injection Pressure (bar)</th>
<th>Fuel</th>
<th>BSFC</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
<th>Soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jeong et al. [17]</td>
<td>500–900</td>
<td>Diesel</td>
<td>na</td>
<td>→</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Fang et al. [18]</td>
<td>600/1000</td>
<td>Diesel</td>
<td>na</td>
<td>↑</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Shimazaki et al. [19]</td>
<td>300–1200</td>
<td>Diesel</td>
<td>↓↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>→</td>
</tr>
<tr>
<td>Kiplimo et al. [20]</td>
<td>800/1400</td>
<td>Diesel</td>
<td>↓</td>
<td>↑</td>
<td>↓</td>
<td>→</td>
<td>↓</td>
</tr>
</tbody>
</table>
With reviewing multiple research studies and summarized in Table 2, the effects of fuel injection pressure on the emission of different species can be seen clearly. It can be found that for both engines, with increased injection pressure, the engine thermal efficiency improved. NOx emissions increased slightly due to the higher combustion temperature. The levels of soot, HC, and CO emissions were determined by the paradoxical effect of better atomization or more serious wall impingement. However, soot emissions were always reduced by increasing the injection pressure.

### 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. Under earlier injection conditions, the fuel-air mixture is mostly formed at the outside of the combustion chamber, and some local rich mixture regions are formed due to the wall-wetting issue. Moreover, the negative work during the compression stroke increases because of the earlier combustion event. These all deteriorate the combustion efficiency and increase the products of incomplete combustion. For HC and CO emissions, the impingement target is an important factor. For middle injection timing, spray wall impingement occurs on the piston head or the outside part of the combustion chamber. For early injection timing, the impingement occurs on the cylinder wall. The different temperature and flow motions of the piston head and cylinder wall directly affect the evaporation process of the wall film. In addition, research results show that when the impingement target is at the bowl–lip area, the fuel-air mixing can be better and low HC and CO emissions can be achieved.

For soot emission, the factor of injection timing has two opposite effects. Earlier injection timing means that longer premixing allows the mixture to reach a lower equivalence ratio for low temperature, which restrains the generation of soot. Moreover, a longer time for soot oxidation is also achieved with earlier injection. On the contrary, spray wall-wetting will form some local rich regions, especially in the crevices, which...
promotes soot generation. Furthermore, the temperature of these wall-wetting regions is generally lower, which prevents the oxidation of soot emission.

As discussed above, the early injection strategy contains single and two-stage injection modes. Thus, in this section, the effects of the injection timing are discussed separately based on the injection mode.

### 4.1 Single Early Injection Timing Effects

Benajes et al.[27] investigated the influence of injection timing on particle emissions with early fuel injection timing of low-temperature diesel combustion. The injection timing was set from 33 to 24 BTDC. Results showed that PM mass and particle number increased with advanced fuel injection timing; the number of particles larger than 50 nm was especially increased. This was mainly because the higher relative levels of liquid fuel deposition on the piston bowl surface formed a locally rich mixture, which promoted soot generation. HC and CO emissions were also increased due to the spray overshoot. Kiplimo et al.[20] studied the impact of injection timing on the performance and emissions of an HCCI diesel engine. The results indicated thermal efficiency and IMEP decreased with advanced injection timing. Injection timing earlier than 30BTDC resulted in higher smoke emissions. This could be affected by the fuel impinging on the piston surface and splashing to the crevices, causing a rich-fuel zone. NOx emissions were lower with earlier injection timing. With the injection timing advanced, CO and HC emissions increased dramatically, owing to the wall-wetting. Figure 4 gives a visualization of the interactions of fuel spray and the surface/wall under various injection timings. Kim and Lee[28] examined the influence of injection timing on the performance and NOx emissions of an HCCI diesel engine. Results showed that IMEP decreased rapidly as the injection timing was advanced beyond 20 BTDC. When the injection timing was set between 30 and 50 BTDC, IMEP was approximately half of that of conventional diesel combustion. NOx emissions were strongly affected by the injection timing. As the injection timing was advanced beyond 30 BTDC, NOx emissions fell near to nearly 0. Kook et al.[29] investigated the effect of injection timing on premixing and combustion in a single-cylinder diesel engine. The injection timing was varied from 50 to 200 BTDC. The results showed that the early injection produced negative work. This negative work decreased as the injection timing was advanced by 70 BTDC due to the extended ignition delay period and retarded combustion phasing, and this caused increased IMEP and thermal efficiency. However, at more advanced injection timing, IMEP and thermal efficiency started to decrease because of the decreased combustion temperature.
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).

<table>
<thead>
<tr>
<th>Author</th>
<th>Injection Timing (° BTDC)</th>
<th>Fuel</th>
<th>BSFC</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
<th>Soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Benajes et al.\cite{27}</td>
<td>33–24</td>
<td>Diesel</td>
<td>na</td>
<td>na</td>
<td>↑</td>
<td>↑</td>
<td>↑</td>
</tr>
</tbody>
</table>
### 4.2 Two-stage Early Injection

In PCCI combustion, a two-stage early injection strategy is utilized: Part of the fuel is first injected into the cylinder to form a homogeneous mixture prior to ignition, and this part undergoes the HCCI type of clean combustion. The remainder of the fuel is injected close to the TDC to control the combustion phase, and this part undergoes conventional combustion.

#### 4.2.1 First Injection Timing Effects

With the advance of first injection timing, the combustion mode transitions from conventional diffusion combustion to premixed HCCI combustion. Earlier first injection timing causes a more homogeneous in-cylinder mixture at the time of ignition since enough time is available to attain a large part of the premixed
mixture, and the combustion process is divided into two stages, as seen in Figure 5. The first stage is the HCCI combustion mode, which contains a low-temperature reaction (LTR) and high-temperature reaction (HTR); the second stage begins just after the start of the second injection with the diffusive combustion because of the short ignition delay. With the advance of the first injection, the interval between the first and second stage combustion is first prolonged and then shortened. This is because with a too-early first injection, the fuel might inject into clearance and squish regions where the temperature is relatively low, and the mixture in these regions is over-lean and hard to be oxidized, resulting in a longer ignition delay.

Figure 5 Representative heat release characteristics of PCCI combustion. L/HTC: low-/high-temperature combustion.

Abdullah et al.\[37\] investigated the effect of first injection timing on a modern V6 common-rail direct-injection diesel engine. The first injection timing was changed from 30° to 21° BTDC, and the second injection timing was fixed at 1.4° after the top dead center (ATDC). Results showed that earlier first injection timing affected the intermediate ignition delay, leading to a complete combustion process. As a result, the early injection timing produced higher in-cylinder pressures, causing higher temperatures and NOx emissions but lower soot emission. Torregrosa et al.\[38\] investigated the sensitivity of NOx and soot emissions to early injection in PCCI diesel engines. The first injection timing was changed from 34° to 26° BTDC, and the main injection timing was kept constant at 18° BTDC. Soot emission generally increased as the early injection timing was brought closer to TDC, and NOx emissions remained significantly lower than conventional diesel engines for all the first injection timing. In addition, BMEP decreased with the early injection timing. Kim et al.\[39\] investigated the effect of a two-stage injection strategy on the combustion and flame characteristics of a PCCI engine. The first injection timing was changed from 70° to 45° BTDC, and the second injection timing was kept constant at 5° ATDC. The results showed that as the first injection was close to TDC, soot, and NOx emissions increased, and BSFC also increased. The best performance occurred when the first injection timing was set at 60° BTDC.

Kook and Bae\[40\] investigated the combustion and emission characteristics of a single-cylinder PCCI engine using two-stage diesel fuel. The first injection timing was varied from 50 to 250 BTDC and the second injection timing was fixed at 20 BTDC. Results showed that extremely advanced timing of 200 and 250 BTDC showed higher IMEP values than retarded first injection timing. The highest IMEP with 200 BTDC was mainly because of the highly increased peak rate of heat release and longer ignition delay and combustion duration, which led to the main heat release stage being closer to TDC.
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. Table 4 provides a summary of multiple studies in terms of engine performance and emissions with a two-stage early injection strategy.

### Table 4. Variation of performance and emissions after advancing the first injection timing (two-stage).

<table>
<thead>
<tr>
<th>Author</th>
<th>First Injection Timing (° BTDC)</th>
<th>Second Injection Timing (° BTDC)</th>
<th>Fuel</th>
<th>BSFC</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
<th>Soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abdullah et al. [37]</td>
<td>30–9</td>
<td>−1.4</td>
<td>Diesel</td>
<td>na</td>
<td>↓↑</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Mobasheri et al. [41]</td>
<td>30–15</td>
<td>9</td>
<td>Diesel</td>
<td>↑</td>
<td>↑</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Torregrosa et al. [38]</td>
<td>34–26</td>
<td>18</td>
<td>Diesel</td>
<td>↑</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Yin et al. [42]</td>
<td>35–10</td>
<td>TDC</td>
<td>Diesel</td>
<td>↑</td>
<td>↓↑</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Jeong et al. [17]</td>
<td>70–20</td>
<td>−5</td>
<td>Diesel</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>→</td>
</tr>
<tr>
<td>Kim et al. [39]</td>
<td>70–45</td>
<td>−5</td>
<td>Diesel</td>
<td>↓</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Yamane and Shimamoto [43]</td>
<td>110–70</td>
<td>na</td>
<td>Diesel</td>
<td>↑</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Kook and Bae [40]</td>
<td>250–50</td>
<td>20</td>
<td>Diesel</td>
<td>↓</td>
<td>→</td>
<td>→</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Yoon et al. [34]</td>
<td>35–15</td>
<td>5</td>
<td>DME</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Yao et al. [44]</td>
<td>42–21</td>
<td>5</td>
<td>n-butanol</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Zhuang et al. [43]</td>
<td>45.5–8.5</td>
<td>−1</td>
<td>Diesel from Direct Coal Liquefaction (DDCL)</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
<td>na</td>
<td>na</td>
</tr>
</tbody>
</table>
4.2.2 Second Injection Timing Effects

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. This was expected, because the charge temperature was too low to burn the second injection fuel.

Coskun et al.\cite{47} experimentally and numerically investigated the effects of second injection variations on combustion and emissions of an HCCI-DI engine. The second injection timing was varied from 30° to 15° BTDC, and the first injection timing was fixed at 240° BTDC. Results showed that the overall combustion and emissions characteristics of the HCCI engine could be directly controlled by second fuel injection timing. Combustion pressure, maximum temperature, and NOx decreased, but HC emission increased by retarding the second injection timing. In addition, computational fluid dynamics (CFD) simulation results showed that combustion began at the fuel-rich zone between the initial homogeneous mixture and the second injected fuel zone. Kook and Bae\cite{40} investigated the combustion and emission characteristics of a single-cylinder PCCI engine using two-stage diesel fuel. The second injection timing was changed from 20° BTDC to TDC, and the first injection timing was fixed at 200° BTDC. Results showed that when the second injection timing was at TDC, two peaks of main heat release appeared, the first from the auto-ignition of premixed charge and the second because the remaining charge was ignited from the second injection. When the second injection timing was set at 15° BTDC, there was only one high peak of main heat release and its highest value could be obtained, so the combustion efficiency was improved. Torregrosa et al.\cite{38} investigated the sensitivity of NOx and soot emissions to early injection in PCCI diesel engines. The second injection timing was varied from 26° to 8° BTDC, and the first injection timing was kept constant at 34° BTDC. They observed that the ignition delay of the second injection decreased as the second injection timing was retarded. Soot emissions generally increased as the second injection timing was brought closer to TDC, while NOx emissions decreased. Besides, BSFC decreased when the second injection was retarded.

Kim et al.\cite{39} investigated the effect of a two-stage injection strategy on the combustion and flame characteristics of a PCCI engine. With the first injection fixed at 60° BTDC, the second injection timing was varied from 5° to -7.5° BTDC. As the second injection timing was retarded, NOx emissions decreased, BSFC increased, and soot did not change much initially but increased later on. The combustion flame was distributed homogeneously in the combustion chamber, and HCCI combustion was noticeable when the second injection timing was retarded after TDC due to the increased time for more homogeneous mixture formation, as seen in Figure 6.
Figure 6. Flame characteristics as a function of second injection timing change. (a–d): different second injection timing, the images of flame change with crank angle.

Table 5 shows a summary of the variation of the performance and emissions of the PCCI engine after retarding the second injection timing. In general, retarding the second injection timing will reduce NOx emissions, but increase soot, HC, and CO emissions. Engine performance deteriorates with retarding of second injection timing due to the shifting of diffusive combustion to later than TDC.

Table 5. Variation of performance and emissions after retarding the second injection timing (two-stage).

<table>
<thead>
<tr>
<th>Author</th>
<th>First Injection Timing (° BTDC)</th>
<th>Second Injection Timing (° BTDC)</th>
<th>Fuel</th>
<th>BSFC</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
<th>Soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coskun et al.</td>
<td>240</td>
<td>30-15</td>
<td>Diesel</td>
<td>na</td>
<td>↓</td>
<td>↓</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Torregrosa et al.</td>
<td>34</td>
<td>26-8</td>
<td>Diesel</td>
<td>↓</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Kook and Bae</td>
<td>200</td>
<td>20-TDC</td>
<td>Diesel</td>
<td>↑</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Kanda et al.</td>
<td>56</td>
<td>18-5</td>
<td>Diesel</td>
<td>↑</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>60</td>
<td>5 to -7.5</td>
<td>Diesel</td>
<td>→</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Kim and Lee</td>
<td>60</td>
<td>TDC to -20</td>
<td>Diesel</td>
<td>↑</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>na</td>
</tr>
</tbody>
</table>
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. For the strategy with early injection timing, with a decreased injection angle, the distance between the nozzle and the cylinder wall increased relatively and more fuel was atomized before reaching the cylinder, leading to reduced wall-wetting fuel mass. For the strategy with middle injection timing, the spray with a narrow injection angle was confined in the piston bowl, and the spray targeting the piston bowl varied with different injection angles. The magnitude and direction of the spray rotation in the bowl were directly affected by the injection angle, as shown in Figure 7. 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. Many researchers have shown that when the spray impinges at the bowl lip bottom edge, the secondary atomization process is enhanced, which benefits the fuel-air mixing. For the second injection of the two-stage injection strategy, using a narrow injection angle against the fuel-air mixing was proved, because the spray targeting moved to the inside part of the piston bowl, where the air motion was weak. Furthermore, the fuel film deposition of the narrow injection angle was stronger, resulting in high soot generation and incomplete combustion.

![Figure 7. Schematic diagrams of the tested combustion chamber and fuel spray: (a) conventional diesel engine; (b) modified engine configuration for early injection.]()

Kim and Lee investigated the effects of a narrow fuel spray angle on improved exhaust emissions in a HCCI diesel engine with an early injection strategy. Two injector nozzles with different spray cone angles (156° and 60°) were used in the study. Results showed that in contrast to the conventional injector, the ISFC indicated a modest decrease when the injection timing was advanced to 50–60° BTDC in the case of a narrow angle injector. In addition, using a dual-injection strategy with narrow angle fuel injection made it possible to reduce CO emissions, maintaining high thermal efficiency and low NOx emissions. Fang et
al.\cite{18} investigated the effects of injection angles on the combustion process using multiple injection strategies in an HSDI optical diesel engine. Two injector tips with different injection angles, 70° and 150°, were used. The results showed that after the first injection, the maximum cylinder pressure and heat release rate were slightly higher for 70° than 150°. However, after the second injection, the cylinder pressure peaks and heat release rates were lower for 70° than 150°. The combustion images for different injection angles and pressures at different crank angles are shown in Figure 8. The nonluminous flame was seen for the first injection of 150°, while two types of flame, nonluminous and luminous film combustion flame, could be seen for 70°. Ignition occurred near the spray tip in the vicinity of the bowl wall for the 150° tip, but it was near the injector tip in the central region of the bowl for the 70° tip. More soot luminosity was observed with the 70° tip due to fuel film combustion. On the other hand, the fuel film combustion led to lower NOx emissions due to its rich mixture. Kim et al.\cite{31} investigated the effects of injection angle on the characteristics of mixture formation and combustion in a PCCI engine using an early multiple injection strategy. Four injection angles (150°, 130°, 100°, and 70°) were tested. Results showed that when the spray impinged on the wall of the combustion chamber, IMEP decreased because of the incomplete combustion due to wall-wetting; IMEP increased as the injection angle decreased. As the injection angle decreased, the mass of fuel impinging on the bowl region increased and the mixture forming in the bowl region became richer, which caused increased smoke.

![Combustion images of injection angles and injection pressures at different crank angles](image)

Figure 8. Combustion images of injection angles and injection pressures at different crank angles\cite{18}.

Table 6 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 6. Variation of performance and emissions after decreasing the injection angle (two-stage).

<table>
<thead>
<tr>
<th>Author</th>
<th>Injection Angle (°)</th>
<th>Fuel</th>
<th>BSFC</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
<th>Soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kim and Lee</td>
<td>60/156</td>
<td>Diesel</td>
<td>↓</td>
<td>→</td>
<td>na</td>
<td>na</td>
<td>na</td>
</tr>
<tr>
<td>Fang et al.</td>
<td>70/150</td>
<td>Diesel</td>
<td>na</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Kim et al.</td>
<td>70–150</td>
<td>Diesel</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Mobasheri and Peng</td>
<td>90–145</td>
<td>Diesel</td>
<td>↓↑</td>
<td>↓</td>
<td>na</td>
<td>na</td>
<td>↓↑</td>
</tr>
<tr>
<td>Vanegas et al.</td>
<td>100–148</td>
<td>Diesel</td>
<td>↑</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Kook and Bae</td>
<td>100/150</td>
<td>Diesel</td>
<td>↑</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Siewert</td>
<td>100–158</td>
<td>Diesel</td>
<td>na</td>
<td>na</td>
<td>↓</td>
<td>↓</td>
<td>↓</td>
</tr>
<tr>
<td>Park et al.</td>
<td>70/156</td>
<td>Bioethanol blended</td>
<td>↓</td>
<td>na</td>
<td>↓</td>
<td>↓</td>
<td>na</td>
</tr>
<tr>
<td>Yoon et al.</td>
<td>60/70/156</td>
<td>DME</td>
<td>↓</td>
<td>→</td>
<td>↓</td>
<td>↓</td>
<td>→</td>
</tr>
</tbody>
</table>

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. 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. Dimethyl ether (DME) is another alternative fuel. Its good ignition capability and high latent heat lead to decreased cylinder temperature in the combustion phase. 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\textsuperscript{[60]}\textsuperscript{[61]}\textsuperscript{[62]}\textsuperscript{[63]}\textsuperscript{[64]}. 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\textsuperscript{[63]}\textsuperscript{[66]}\textsuperscript{[67]}\textsuperscript{[68]}. 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\textsuperscript{[69]}\textsuperscript{[70]}.

Fang et al.\textsuperscript{[71]} investigated different blending ratios (20–100%) of biodiesel combustion in an optical HSDI diesel engine under low-load premixed combustion conditions using the early injection strategy. Results showed that fuel impingement on the wall was observed for all ratios. The liquid penetration became longer and fuel impingement was stronger with increased biodiesel ratio; also, the ignition delay became longer and heat release curves became lower and broader. This could be explained by the higher boiling point and lower cetane number of biodiesel. Except for B0, soot luminosity increased with increasing biodiesel ratio. This might be because of the low volatility of biodiesel results in locally rich regions with higher soot luminosity, as shown in Figure 9. NOx emissions first decreased with increasing biodiesel ratio; then, after the ratio passed a certain value, NOx emissions increased. This is because of the trade-off between ignition delay and oxygen content. Park et al.\textsuperscript{[63]} investigated the effects of bioethanol-blended diesel fuel on combustion and emission characteristics in an early injection diesel engine. The blending ratio of the bioethanol varied from 10% to 30%. Results showed that an increased bioethanol blending ratio extended the ignition delay due to lower cetane number and the decreased gas temperature caused by the evaporation of bioethanol with large latency. The difference in ignition delay between pure diesel and diesel–bioethanol blended fuels became larger under early injection conditions. The bioethanol–diesel blending caused a small decrease in soot emission because of the high oxygen content, and reduced NOx emission because of the low combustion temperature caused by the high heat of evaporation of bioethanol fuel and lower heating value. However, HC and CO emissions increased with an increased bioethanol blending ratio.

![Figure 9. Combustion images at different crank angles under various biodiesel blending ratios\textsuperscript{[71]}. SOI: start of injection.](image)

Agarwal et al.\textsuperscript{[72]} reported the effects of 10%, 20%, and 50% Karanja biodiesel blends on injection rate, atomization, engine performance, emissions, and combustion characteristics of a common rail direct-injection (CRDI)-type fuel injection system evaluated in a single cylinder. The results showed that as the
blend ratio increased, BSFC increased obviously. As for emissions, NOx decreased, but HC and CO increased because the higher blend ratio caused the inferior mixing of fuel with air. Guedes et al.\textsuperscript{[23]} studied the performance and combustion characteristics of a compression ignition engine running on (diesel biodiesel ethanol) DBE blends. The engine was fueled with B15E5, B15E10, and B15E15 (B, biodiesel; E, ethanol). At the same speed of torque and injection timing, results showed that BSFC increased with increased ethanol content due to the lower heating value.

Table 7. Variation of performance and emissions after increasing the blending ratio of alternative fuels.

<table>
<thead>
<tr>
<th>Author</th>
<th>Blending Ratio (%)</th>
<th>Fuel</th>
<th>BSFC</th>
<th>NOx</th>
<th>HC</th>
<th>CO</th>
<th>Soot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fang et al.\textsuperscript{[71]}</td>
<td>20–100</td>
<td>Biodiesel</td>
<td>na</td>
<td>↓↑</td>
<td>na</td>
<td>na</td>
<td>↑</td>
</tr>
<tr>
<td>Park et al.\textsuperscript{[63]}</td>
<td>10–30</td>
<td>Bioethanol</td>
<td>na</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>→</td>
</tr>
<tr>
<td>Liu et al.\textsuperscript{[62]}</td>
<td>30–70</td>
<td>Gasoline</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>na</td>
<td>↓</td>
</tr>
<tr>
<td>Ma et al.\textsuperscript{[74]}</td>
<td>68–84</td>
<td>Gasoline</td>
<td>na</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
<td>↓</td>
</tr>
<tr>
<td>Yao et al.\textsuperscript{[44]}</td>
<td>0–15</td>
<td>n-Butanol</td>
<td>↑</td>
<td>na</td>
<td>na</td>
<td>↓</td>
<td>↓</td>
</tr>
</tbody>
</table>

Table 7 shows a summary of the variation of performance and emissions of HCCI and PCCI engines after increasing the blending ratio of alternative fuels. In general, for oxygenated fuel, the high heat of evaporation and lower heating value leads to reduced combustion temperature, which is beneficial for reducing NOx emissions, but is not good for the oxidation of HC, CO, and soot emissions. However, the high oxygen content of oxygenated fuel helps to consume soot precursors and HC and CO emissions in the over-rich region. Besides, the liquid penetration of the spray becomes longer with increased oxygenated because of the change of the physical properties of injected fuel, resulting in a more serious wall-wetting phenomenon. So the emission characteristics of fuel with different blending ratios are affected by the above factors. For gasoline–diesel blended fuel, the increased gasoline ratio prolongs ignition delay and promotes better fuel-air mixing. In addition, the higher fuel vaporization decreases the cylinder temperature, which results in reduced NOx and soot. However, the increased crevice flow mass and lower temperature lead to increased HC and CO, but wall-wetting is reduced because of the short penetration of the gasoline–diesel spray.

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 8.
8. Future Research Directions

From the review of the published work on the early injection parameters of HCCI and PCCI engines, the following interesting topics are identified for investigation in future research:

- Methods to limit or avoid the wall-wetting problem caused by early injection strategy, including an improved injection system or multiple-pulse injection strategy.

- Accurate spray-wall impingement mechanism, especially the fuel, including alternative fuel, because the physical and chemical characteristics changed with the addition of alternative fuel.

- The effect of the impingement target on mixture formation and emission distribution in the cylinder; in addition, optimization of the impingement target should consider the factors of injection timing, injection angle, and piston structures simultaneously.

- The effects of the early injection parameters on combustion noise radiation, which is expected to gain interest with the development of HCCI and PCCI engines.

- The interrelationship between early injection strategy and modern catalytic devices, such as Diesel Particulate Filter (DPF), Selective Catalytic Reduction (SCR), and Lean NOx Trap (LNT), especially with respect to particle number concentration and distribution, but also possibly due to durability issues.

- Early injection strategy combined with reactivity controlled compression ignition (RCCI), research and analysis of the impact of early injection strategy on RCCI engine, including injection timing, injection pressure, injection angle and so on.

- Combining different types of lubricating oils, one can study the influence of early injection strategies on engine performance and emission characteristics.

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Keywords

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

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