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A Study on the Characteristics of Spray and Combustion in a HCCI Engine according to Various Injection Angles and Timings

Hyungmin Kim, Jeaduk Ryu
Graduate School of Hanyang University,
Department of Mechanical Engineering, Hanyang University
1271 Sal-dong, Sangrok-gu, Gyeonggi-do 426-791, Korea
Kihyung Lee*
Department of Mechanical Engineering, Hanyang University,
1271 Sal-dong, Sangrok-gu, Gyeonggi-do, 426-791, Korea

Premixed diesel engines have the potential to achieve a more homogeneous, leaner mixture near TDC compared to conventional diesel engines. Early studies have shown that the fuel injection timing and injection angle affect the mixture formation in a HCCI (Homogeneous Charge Compression Ignition) engine. Therefore in this study, we investigated the relationship between combustion and mixture formations accordance with injection conditions in a common rail direct injection type HCCI engine using an early injection strategy. From this results, we found that the fuel injection timing and injection angle affect the mixture formation and in turn affect combustion in the HCCI engine. In addition, this study revealed that the injection angle of 100° is effective to reduce smoke emission without any sacrificing power in the early injection case.

Key Words : Homogeneous Charge Compression Ignition Engine, Emission, IMEP, Injection Angle, Injection Timing

Nomenclature

r_d	: Droplet radius
T	: Taylor number $(=z(We)^{0.5})$
Z	: Ohnesorge number $(=(We)^{0.5}\mathrm{Re}^{-1})$
We	: Weber number
σ	: Surface tension
U_r	: Relative velocity between ambient and drop
m_d	: Droplet mass
A_d	: Droplet frontal area
Sh	: Sherwood number
D_{AB}	: Mass diffusivity
ρ_v	: Vapor density
ρ_a	: Ambient density
$P_{v,s}$	: Partial pressure at the droplet surface
$P_{v,\infty}$	: Partial pressure at the ambient
$C_{p,d}$	: Specific heat of liquid
Nu	: Nusselt number
K_m	: Mixture thermal conductivity
h_{hg}	: Latent heat of evaporation
T_d	: Droplet temperature
We_{in}	: Weber number of the impinging droplet
T_{Leid}	: Leidenfrost temperature
IMEP	: Indicated Mean Effective Pressure
FSN	: Filter Smoke Number

1. Introduction

The demand for automobiles with lower emissions and higher thermal efficiency has been increasing worldwide. Especially a diesel engine with high thermal efficiency is very attractive ;

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* Corresponding Author,
E-mail : hylee@hanyang.ac.kr
TEL : +82-31-418-9393; **FAX** : +82-31-406-5550
Department of Mechanical Engineering, Hanyang University, 1271 Sal-dong, Sangrok-gu, Gyeonggi-do, 426-791, Korea. (Manuscript **Received** May 12, 2006; **Revised** October 21, 2006)

however, increased emissions such as NO_X from the local high temperature reaction region and particulate matter during diffusion combustion, both characteristic of diesel engines, are emerging as problems. Therefore some research involving internal combustion engines focuses on the development of lower-polluting technology, known as 'clean combustion', that can satisfy stringent emissions restrictions. To meet this demand, HCCI (Homogeneous Charge Compression Ignition) combustion, which ignites a uniform homogeneous charge in the combustion chamber using a homogeneous mixture spray system that can mix fuel and air sufficiently, is drawing attention (Najt and Foster, 1983 ; Iwabuchi et al., 1999). Research on HCCI combustion that would satisfy efficiency and emissions standards of a diesel engine is in progress, but the conventional diesel engine injection system has not decreased emissions as much as expected due to the collision of the spray with the wall when the fuel injected into cylinder at the early stage of compression stroke.

Therefore in this research, spray behavior, combustion and emission characteristics in accordance with injection angle and timing are identified using a high-pressure diesel injector with varying injection angles and injection timing for HCCI combustion are suggested.

2. Experimental Apparatus and Procedures

2.1 Experimental apparatus

Figure 1 shows a diagram of a common rail injection type HCCI single cylinder engine. As shown in the figure, a common rail injector was fitted vertically in the center of the cylinder head ; a coolant and engine oil supplier and a 3 kW heater to control temperature were also installed. The engine was operated with a constant speed using a 30 kW AC motor. To measure position of the piston, an 1800 pulse encoder was fixed to the crank shaft and a TDC sensor to the cam shaft. To control injection pressure, a PCV (Pressure Control Valve) was used for the common rail. A counter board controlled injection timing and injected fuel quantity. In addition, combustion pressure was measured by installing a pressure sensor in the combustion chamber to identify HCCI combustion. Test injectors with various injection angles such as 150°, 130°, 100° and 70° were used in this study to investigate the effect of spray angle on wall wetting phenomenon. The detailed specifica-

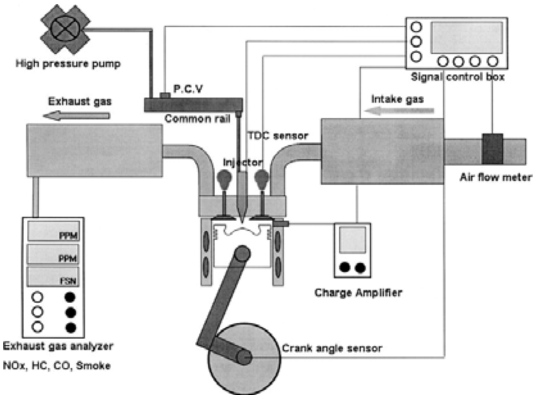
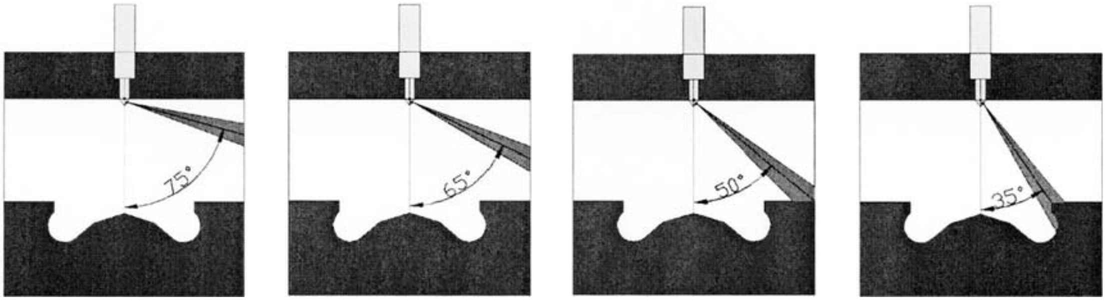


Fig. 1 Schematic of common rail injection type HCCI single cylinder engine



(a) Injection angle : 150° (b) Injection angle : 130° (c) Injection angle : 100° (d) Injection angle : 070°

Fig. 2 The definition of injection angle for test injectors tions of test injector were shown in Figure 2.

2.2 Spray simulation

The numerical simulation of a spray injected from a common rail type injector was performed using the VECTIS 3.7 program (Ricardo Co. Ltd, 2003). We assumed that the calculation domain was a cylinder with 200 mm in diameter and 200 mm in height. We selected 50000 as the calculation mesh in order to prevent a wall collision with the cylinder. The injection velocity and discharge coefficient were calculated using the experimental data of the injection rate (Ryu et al., 2004), the initial S.M.D. value postulated nozzle diameter, and an X-square distribution. We also used the breakup model developed by the Liu-Mather-Reitz model (Liu et al., 1993). The breakup of the injected liquid was accounted for using surface wave breakup. From the Kelvin-Helmholtz surface tension wave theory, the wavelength and frequency of the fastest growing waves are expressed as follows:

$$\Lambda_{KH}=\frac{9.02r_d(1+0.45(Z)^{0.5})(1+0.4T^{0.7})}{(1+0865We^{1.67})^{0.6}} \quad (1)$$

$$\Omega_{KH}=\frac{(0.34+0.385We^{1.5})}{((1+Z)(1+1.4T^{0.6}))}\sqrt{\frac{\sigma}{\rho_d r_d^3}} \quad (2)$$

The newly formed droplet size is assumed to be proportional to the above Kelvin-Helmholtz wavelength:

$$r_{d,stable}=B_0\Lambda_{KH} \quad (\Lambda_{KH}\leq r_d) \quad (3)$$

$$r_{d,stable}=\min\left[\left(\frac{3\pi r_d^2U_r}{2\Omega_{KH}}\right)^{1/3},\left(\frac{3r_d^2\Lambda_{KH}}{4}\right)^{1/3}\right] \quad (4)$$
$$(\Lambda_{KH}\geq r_d,\ once)$$

The constant B_0 is set at 0.6. For Kelvin-Helmholtz breakup, the droplet lifetime is

$$\tau_b=\frac{3.78B_1r_d}{\Omega_{KH}\Lambda_{KH}} \quad (5)$$

where the breakup time constant B_1 is 10.

In addition, a spray calculation was conducted in a combustion chamber that simulates the geometry of the real HCCI engine to analyze spray pattern and evaporation characteristics using the spray model. The engine geometry has a compression ratio of 17.5, bore of 91 mm, and stroke of 96 mm. We chose 220 deg as the calculation start time which corresponds to both intake and exhaust valves closed, and we chose TDC which corresponds to combustion as the end time. Further, the engine running condition was 1400 rpm and the swirl ratio produced from the intake port was 2.0.

To evaluate fuel evaporation, heat transfer and temperature calculations were added. Equations (6) and (7) express the mass and temperature of a droplet (Ricardo Co. Ltd, 2003).

$$\frac{dm_d}{dt}=-A_dSh\frac{D_{AB}}{D_d}\rho_v\ln\frac{(p-p_{v,\infty})}{(p-p_{v,s})} \quad (6)$$

$$m_d\frac{dC_{p,d}T_d}{dt}=-A_dNu(T_d-T)k_mF_z+h_{hg}\frac{dm_d}{dt} \quad (7)$$

The spray impingement model proposed by Gosman et al. was used to evaluate spray characteristics. According to the We_{in} and T_{Leid}, the stick, rebound, spread, and splash conditions did occur after spray impingement. The roughness effect of the combustion chamber was ignored (Bai and Gosman, 1995).

2.3 Experimental and simulation procedure

In this research we evaluated the effects of the geometry of a piston and collision location of spray on the formation of mixture by performing a spray simulation according to the injection angle and injection timing. Then we studied engine performance and emissions accordingly. We also conducted a combustion analysis using the experimental device as shown in Figure 1 to evaluate the combustion and output performance of the

Table 1 Experimental conditions

Engine speed	1400 rpm
Injection pressure	100 MPa
Injection quantity	7.5 mm^3~26 mm^3
Injection timing	BTDC 180 deg~TDC
Injection angle	70°, 100°, 130°, 150°
Hole diameter	0.168 mm
Intake Temperature	300 K
Intake Pressure	Natural aspiration

HCCI engine, measured NO_x, CO and HC with the emission gas analyzer (Horiba Company) to evaluate emission performance, and evaluated the density of smoke using a smoke meter (AVL Company). The engine speed and injection pressure were fixed at 1400 rpm and 100 MPa for the experiment detailed in Table 1, and the effects of injection angle and injection timing were evaluated.

3. Experimental Results and Discussion

3.1 Combustion characteristics of the early injection type HCCI engine

3.1.1 Combustion characteristics according to injection timing

Figure 3 shows the characteristics of IMEP according to the injection timing at an injection angle of 150°. IMEP increases as the injection timing progresses and when the injection timing approaches TDC, knocking occurs, which corresponds to the noise and rapid rising rate of the cylinder pressure. This characteristic becomes more evident as the amount of injected fuel increases. However, in the case of early injection, IMEP for homogeneous combustion region is about 50% of the conventional diesel combustion region. This is thought to be the result of the fact that the diesel fuel used in this study reached self-ignition temperature before TDC when the fuel was injected early, due to the low ignition temperature of the diesel fuel. From this result, we expected that it is necessary to delay the start of auto ignition for obtain sufficient power of a HCCI engine.

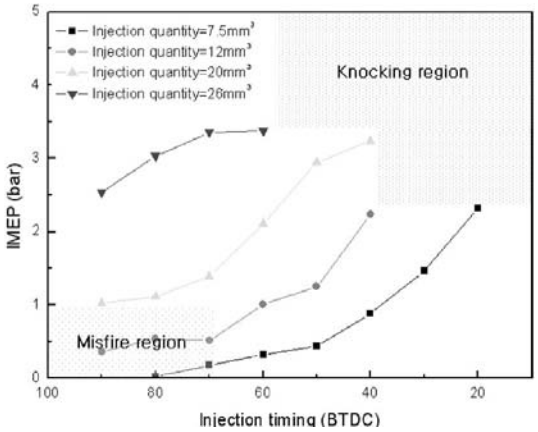
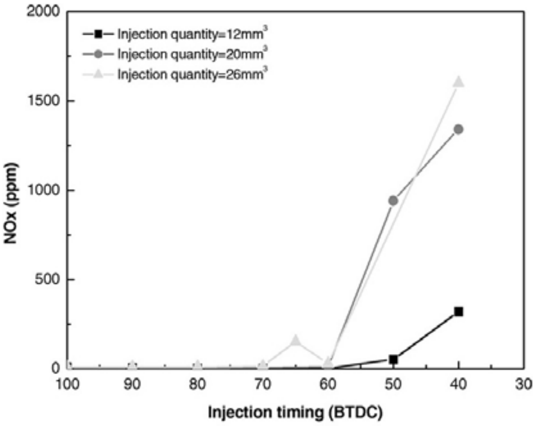


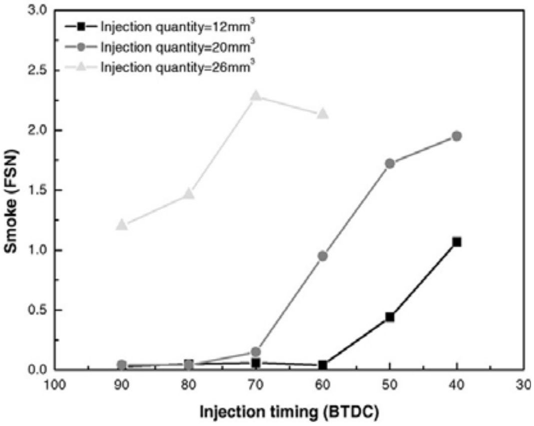
Fig. 3 IMEP characteristics of HCCI combustion according to injection timing

3.1.2 Characteristics of emission according to injection timing

Figure 4 shows the emission characteristics according to injection timing with an injection angle of 150°. The maximum emission of NO_x occurs in the knocking region and then decreases as the injection timing advances. It does not occur prior to BTDC 60° and this tendency does not vary with injected fuel amount. It is thought that



(a) NO_x emission



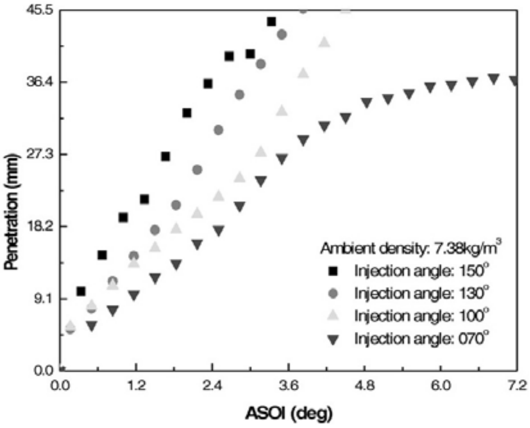
(b) Smoke emission

Fig. 4 Characteristics of emission according to injection timing and quantity the generation of NO_x reaches a maximum value in the knocking region due to sudden heat release because the generation amount of NO_x is proportional to the temperature. The generation of NO_x decreases over BTDC 60° injection timing in the homogeneous combustion region due to the low-temperature combustion. The smoke generation characteristics according to the injection timing show that the smoke is not generated during early injection and the generation of the smoke increases as the injection timing approaches TDC. The increase of the equivalence ratio caused the increase of the smoke independently of the injection timing. This resulted from collision of the spray on the wall and the heterogeneous mixture because a 150° injection angle nozzle used in this study has a wide spray angle. Therefore, to realize HCCI combustion using the early injection method, use of a narrow angle injector (Walter and Gatellier, 2002), collision of the spray on the combustion chamber, and the mixture distribution characteristics (Nandha and Abraham, 2002) should be checked.

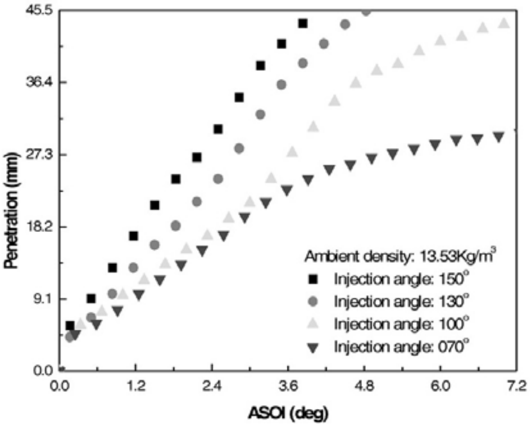
3.2 Characteristics of spray according to the various injection angles and injection timings

3.2.1 Characteristics of spray according to the various injection angles

Figure 5 shows the comparison of penetration length according to ambient density, which corresponds to the cylinder pressure at injection timing BTDC 70～50° conditions. As the injection angle narrowed, the spray penetration length decreased as under view of spray. In an ambient density of 13.53 kg/m^3, the spray did not collide with the wall of the combustion chamber and the spray penetration became even shorter in the real combustion chamber (bore is 91 mm) considering the ambient temperature and flow field.



(a) Lower ambient density

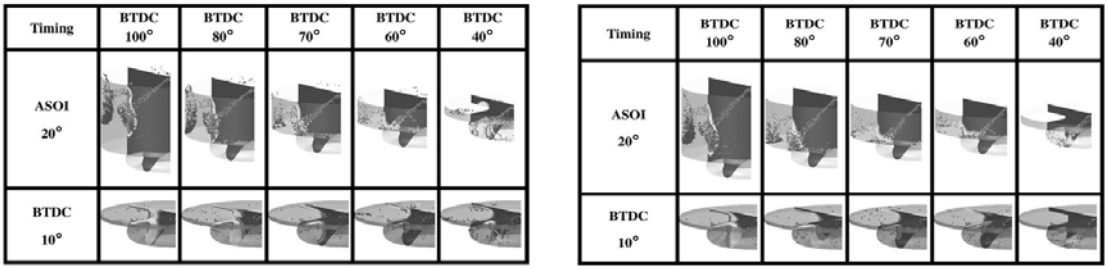


(b) Higher ambient density

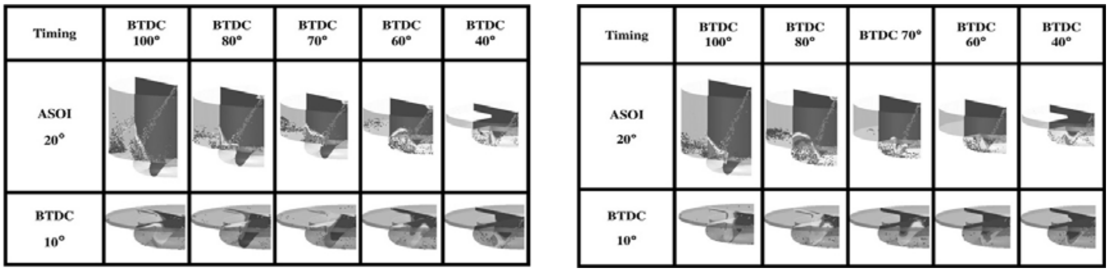
Fig. 5 Comparison of penetration length between various injection angles

3.2.2 Air-fuel distribution characteristics according to various injection angles and injection timings using spray simulation method

Figure 6 compares the air-fuel distribution characteristics in the collision location and ignition timing (BTDC 10°) of the spray according to the injection timing for each injection angle. In the case of early injection in which spray directly impinges on the wall, a rich mixture is formed on the wall and a lean mixture is formed in the center of the combustion chamber and the piston bowl zone. In the cases of 70° injection angle at BTDC 80° injection timing and 100° injection angle at BTDC 60° injection timing, distribution of the mixture was generally uniform throughout the entire combustion region when the spray collision occurred in the upper piston and the border region of the piston bowl. From this result we can conclude that the spray collision location affects the mixture distribution.



(a) Injection angle : 150° (b) Injection angle : 130°



(c) Injection angle : 100° (d) Injection angle : 70°

Fig. 6 Air-fuel distributions according to various injection angles and injection timings

3.3 Combustion characteristics according to various injection angles and injection timings

3.3.1 Flame characteristics according to various injection angles and injection timings

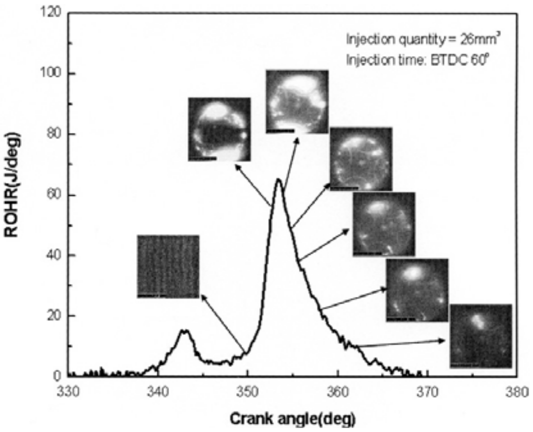
Figure 7 shows the flame developing process according to the injection angle for early injection timing. In the case of an injection angle of 150°, the mixture existed at the corner of the combustion chamber and upper part of the piston, and a bright flame was seen around the bowl zone. In the case of an injection angle of 100°, the spray collides with the corner region of the bowl in piston and forms a relatively uniform mixture, and the combustion chamber shows a blue flame in general. In the case of an injection angle of 70°, the mixture was distributed in the bowl zone and the combustion chamber showed a yellow flame. It is thought that the strength of the flame is related to the heterogeneous mixture formation that can produce the smoke.

3.3.2 Performance characteristics according to various injection angles and injection timings

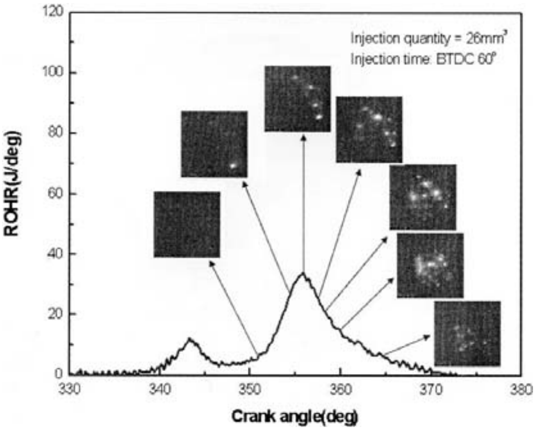
Figure 8 shows the IMEP characteristics of premixed combustion according to varying injection angle. During the injection when the spray collides with the wall of the combustion chamber, IMEP decreases because the combustion was not completed due to wall wetting. When the spray collided with the upper piston and the bowl zone border, IMEP increased because the mixture was distributed uniformly in the whole combustion chamber. When the spray collided with the bowl zone of the piston directly, the mixture was distributed densely in that region and IMEP showed the maximum value with knocking phenomena.

3.2.3 Emission characteristics according to various injection angles and injection timings

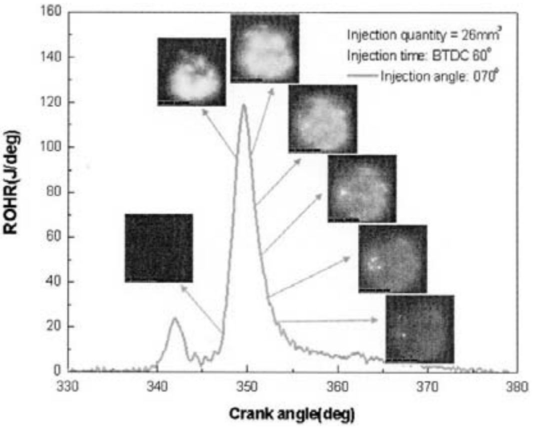
Figure 9 showed the smoke characteristics according to various injection angles and timings. The generation characteristics of smoke coincide with the characteristics of IMEP and it is thought that there is a close relationship between the collision location of the spray and formation of the mixture. In particular, in the case of dense formation of the mixture locally in the combustion chamber, the generation of smoke increased, and when the mixture was distributed uniformly in the bowl zone, the generation of smoke decreased.



(a) Injection angle : 150°



(b) Injection angle : 100°



(c) Injection angle : 70°

Fig. 7 Comparison of flame developing process with three injection angles (Injection timing : BTDC 60°, Injection quantity : 20 mm³)

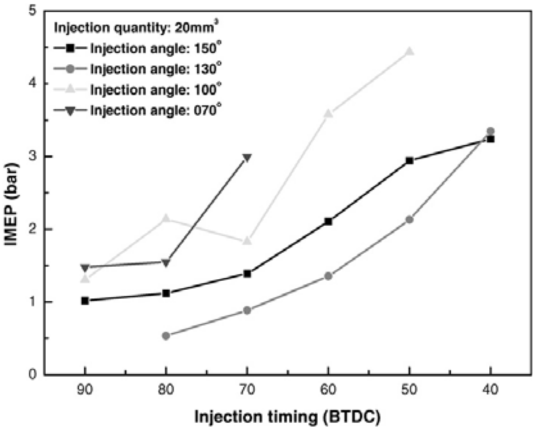


Fig. 8 Characteristics of IMEP according to various injection angles of HCCI combustion

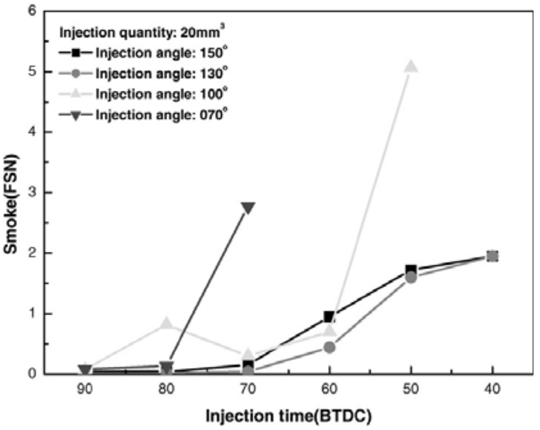


Fig. 9 Characteristics of smoke according to various injection angles and timings

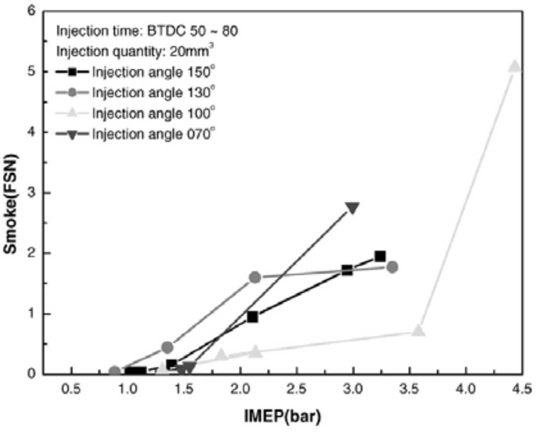


Fig. 10 Characteristics of smoke according to IMEP

Figure 10 shows the smoke characteristics according to IMEP. In general, when IMEP increased, the amount of smoke tended to increase. This shows that a rich mixture is good for the performance of the engine, but also increases the generation of smoke. But when the injection angle is 100°, smoke is less than FSN1 even if IMEP is over 3.5bar. Therefore, in the case of early injection, the injection angle of 100° is effective to reduce smoke without any sacrificing IMEP.

4. Conclusions

In this research, we investigated the spray and combustion characteristics of the HCCI engine according to the injection angle and injection timing using the early direct injection system and came to the following conclusions.

(1) Early injection-type HCCI combustion using a conventional diesel injector led to low IMEP and increased smoke due to wall wetting.

(2) In the case of direct collision of the spray on the wall, a rich mixture is formed on the liner wall of the combustion chamber regardless of the injection angle and a lean mixture formed at the center of the combustion chamber and around the piston bowl zone.

(3) In the cases that spray collision occurred at the upper piston and the border of the bowl zone of the piston, the distribution of the mixture was uniform throughout the entire combustion chamber.

(4) IMEP and smoke showed proportional tendencies. However, when the injection angle was 100°, smoke was less than any other cases. Thus, this condition is effective to reduce smoke without any sacrificing power.

Acknowledgments

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