Effect of the Ethanol Injection Moment During Compression Stroke on the Combustion of Ethanol - Diesel Dual Direct Injection Engine

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Abstract. A set of GDI system is installed on a F188 single-cylinder, air-cooled and direct injection diesel engine, which is used for ethanol injection, with the injection time controlled by the crank angle signal collected by AVL angle encoder. The injection of ethanol amounts to half of the thermal equivalent of an original diesel fuel. A 3D combustion model is established for the ethanol - diesel dual direct injection engine. Diesel was injected from the original fuel injection system, with a fuel supply advance angle of 20°CA. The ethanol was injected into the cylinder during compression process. Diesel injection began after the completion of ethanol injection. Ethanol injection starting point of 240°CA, 260°CA, 280°CA, 300°CA and 319.4°CA were simulated and analyzed. Due to the different timing of ethanol injection, the ignition of the ethanol mixture when diesel fires, results in non-uniform ignition distribution and flame propagation rate, since the distribution and concentration gradients of the ethanol mixture in the cylinder are different, thus affecting the combustion process. The results show that, when ethanol is injected at 319.4°CA, the combustion heat release rate and the pressure rise rate during the initial stage are the highest. Also, the maximum combustion pressure, with a relatively advance phase, is the highest. In case of later initial ethanol injection, the average temperature in the cylinder during the initial combustion period will have a faster rise. In case of initial injection at 319.4°CA, the average temperature in the cylinder is the highest, followed by 240°CA ethanol injection. In the post-combustion stage, the earlier ethanol injection will result in higher average temperature in the cylinder and more complete fuel combustion. The injection of ethanol at 319.4°CA produces earlier and highest NOX emissions.

1. Introduction

The application of ethanol, as a renewable alternative energy in gasoline engine, is matured; however, as it is not mutually soluble with diesel, it has more forms in application in diesel engine, including a small proportion of ethanol mixed with diesel frequently [1-4], covering pre-mixing or real-time mixing [5]. In case of ethanol injection in the inlet manifold or near the air inlet, it will be ignited by burning diesel [6]; in case of ethanol injection in the inlet manifold or the cylinder, it will be compressed combustion [7, 8].

Jilin University conducted the study of the ethanol - diesel dual direct injection previously [9, 10]. A set of mechanical pump injection system is installed on the diesel engine, with ethanol injection and diesel injection respectively for original injection system and new injection system. The dual injection system can reach the performance and fuel economy of the original diesel engine with ethanol and diesel. However, due to restrictions of the mechanical pump injection system, ethanol injection starting point is 1°CA behind the diesel injection starting point, diffusion accounts for the main part during ethanol combustion, and HC and CO emissions significantly increase when compared with the original diesel engine.

Therefore, we install the electronic control gasoline injection system on the single cylinder diesel engine, adopt ethanol injection during compression stroke of the electronic control injection system and diesel injection by the original pump injection system, and establish a 3D combustion model, so as to study the impact of ethanol injection moment during compression on the mixed ethanol formation and combustion process of the ethanol - diesel dual direct injection engine.

2. Engine prototype

The engine is modified based on KS7500SE diesel generator, and main technical parameters of the engine are shown in Table 1. 0# diesel is purchased from one PetroChina gas station, and fuel ethanol (content≥99.5%) is produced by Chongqing Chuandong Chemical (Group) Co., Ltd. The main physical and chemical indicators are shown in Table 2.

Table 1. Summary of engine specifications

Parameters	Value
Type	Vertical, air cooled, natural aspirating, direct injection, four-stroke
Cylinder bore × stroke / mm×mm	88×75
Length of the connecting rod/mm	115
Compression ratio	20.8
Rated rotation speed / $r\cdot min^{-1}$	3000
Combustion chamber type	Type ω
Diesel supply advance angle (ºCA in front of the TDC)	21
Inlet valve closing (ºCA behind the BDC)	54
Exhaust valve open (ºCA in front of the BDC)	54
Number of nozzles of the diesel injector	4
Diameter of nozzles of the diesel injector/mm	0.32
Number of nozzles of the ethanol injector	6
Diameter of nozzles of the ethanol injector/mm	0.183

Table 2. Physical and chemical properties of fuel

Parameters	Ethanol	$0^{\#}$ Diesel
Density (30℃) / $g\cdot cm^{-3}$	0.789	0.839
Kinematic viscosity (30℃) / $mm^2\cdot s^{-1}$	1.152	3.321
Cetane number	8.0	49.1
Oxygen content / %	34.78	0.00
Lower calorific value of fuel / $MJ\cdot kg^{-1}$	26.80	42.50

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3. Combustion Model

The TDC geometric model of the combustion chamber is drawn by ProE software and divided by Hypermesh software, and AVL FIRE is also imported to set up the dynamic mesh and conduct computation and post-processing analysis. The diesel injector has 4 uniform holes, and ethanol injector has 6 non-uniform holes. As the angle between the hole injection direction of two injectors and the cylinder section is different, the whole combustor chamber is adopted for model. The injection location and fuel spray distribution are shown in Figure 1. In order to describe the nephogram in post-processing of the example, two sections are defined (section A passes through the diesel injector center and section B passes through the ethanol injector center, and these two sections are the symmetrical sections of the injection fuel spray). The area close to the nozzle and boundary is densified, with 110,496 meshes at TDC and 348,096 meshes at BDC. The combustion chamber mesh at TDC is shown in Figure 2. The kinetic calculation of chemical reaction is carried out with the FIRE's own standard ethanol and diesel transportation model, and the main computational model selection is shown in Table 3.

Five conditions with ethanol injection earlier than diesel injection are simulated with the combustion model (with the diesel injection starting point at 344°CA, and ethanol injection starting points at 240°CA, 260°CA, 280°CA, 300°CA and 319.4°CA), and the final case is that the end moment of the ethanol injection is just the diesel injection starting point. This paper focuses on the comparison and analysis of the mixed gas formation in the cylinder and combustion process under conditions of different ethanol injection starting points. The test results of each case will be analyzed separately.

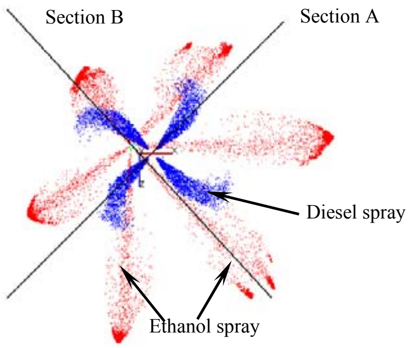


Figure 1. Diesel and ethanol injection position and fuel spray

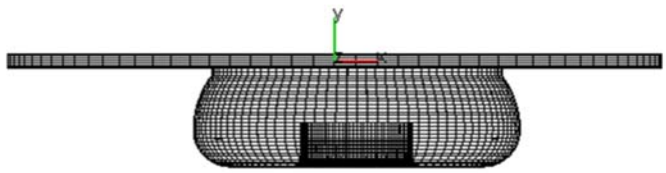


Figure 2. Combustion chamber mesh at TDC

Table 3. Computational models

Computational Model	Selection
Turbulence model	K-Zeta-F
Fuel wall interaction model	Bai Gosman
Fuel evaporation model	Multi-component
Fuel spray breakup model	KHRT
Combustion model	Coherent Flame Model
Self-ignition model	Two-Stage
Nitrogen oxide model	Extended Zeldovich+prompt+fuel

4. Combustion Simulation Results and Analysis

Figure 3, Figure 4 and Figure 5 show the cylinder pressure and combustion heat release rate, average temperature in the cylinder and NO mass fraction under conditions of five ethanol injection starting points.

4.1. Cylinder Pressure and Combustion Heat Release Rate

The combustion heat release curve in Figure 3 shows that the combustion heat release starting point is almost the same. In case of the initial ethanol injection moment at 240°CA and 260°CA, the heat release rate curve is smaller. In case of the initial ethanol injection moment at 280°CA, the peak heat release rate is the minimum but the duration is long. In case of the initial ethanol injection moment at 300°CA and 319.4°CA, the heat release rate curve is similar, the initial combustion heat release rate curve is steeper, and the combustion heat release stage is relatively concentrated, and in case of the initial ethanol injection moment at 319.4°CA, the initial combustion heat release rate curve is the steepest, and the maximum combustion heat release rate is significantly higher than that of other conditions. The cylinder pressure curve shows that, in case of initial ethanol moment at 240°CA, 260°CA and 280°CA, the highest combustion pressure and its corresponding phase are smaller. In case of initial ethanol moment at 300°CA and 319.4°CA, the cylinder pressure curve is relatively similar, the pressure rise curve is steep, and the maximum combustion pressure is higher than that of first three conditions, and the corresponding phase is earlier. In case of initial ethanol moment at 319.4°CA, the cylinder pressure is obviously higher than that of other conditions.

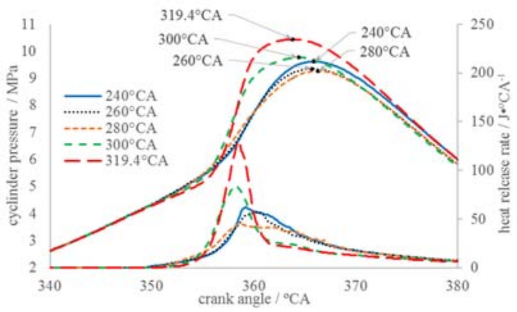


Figure 3. Cylinder pressure and combustion heat release rate

4.2 Average Temperature in the Cylinder

Figure 4 shows that, in case of initial ethanol moment at 300°CA and 319.4°CA, the average temperature in the cylinder has a faster rise. The average temperature in the cylinder is the highest in case of initial ethanol moment at 319.4°CA, followed by 240°CA ethanol injection. In the post-combustion stage, the average temperature in the cylinder is higher in case of earlier ethanol injection, and the earlier injection brings the longer time for the ethanol gasification, which is conducive to the full combustion and heat release.

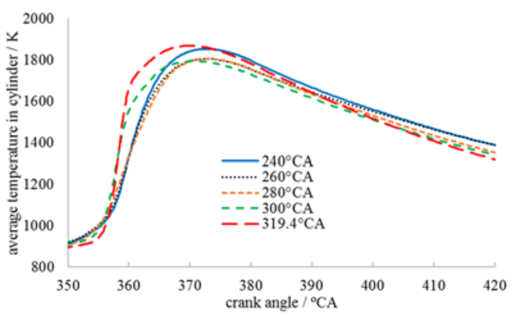


Figure 4. Average Temperature in the Cylinder

4.3 NO Concentration

Figure 5 shows that, in case of initial ethanol moment at 319.4°CA, NO is generated earlier and emission is the maximum, and the rest of the conditions reflects higher NO mass concentration in case of early injection. In case of initial ethanol moment at 260°CA and 280°CA, NO concentration difference is small, and NO is frozen after the rapid combustion stage. According to Figure 5, higher average temperature in the cylinder brings higher NO concentration.

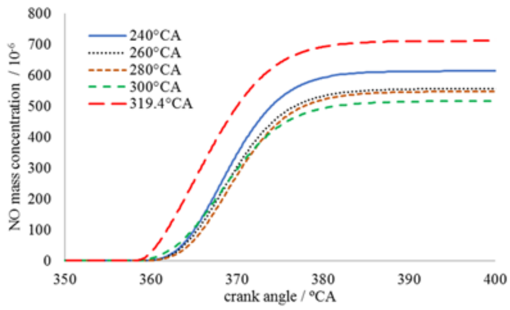
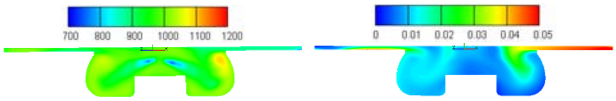


Figure 5. NO mass concentration in the cylinder

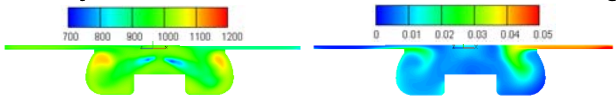
4.4 Discussion and Analysis

The temperature and pressure in the cylinder at the ethanol injection moment will affect the spray cone, penetration distance, initial particle size and atomization effect of the ethanol spray [11,12]. The position of the piston at the injection moment determines the position of the ethanol spray wall interaction position and thus affects the spatial distribution of the mixed ethanol [13]. Along with the piston moving up, the gas flow in the cylinder becomes stronger, so the flow of the gas in the cylinder at the ethanol injection moment also affects the formation of the mixed ethanol [14,15].

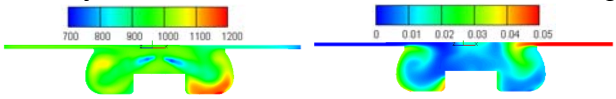
Figure 6 shows the temperature distribution and the ethanol concentration distribution in the cylinder when the ignition starting point is 354°CA (extracted from the section A where the diesel spray is located in Figure 1). Figure 6 shows that, the first burning area is located in the outer layer spraying diesel earlier. The diesel in this part stays the longest in the cylinder and its contact with the air is the most sufficient, therefore, it is easy to form premixed gas. In addition, along with the diesel heating and evaporation, it absorbs the gas heat of involved areas and cools down the fuel spray center. However, as the gas in the outer layer of the fuel spray has higher temperature, the outer layer spraying diesel earlier reaches the burning conditions firstly. The comparison between temperature and ethanol concentration shows that, the initial burning area is of lower ethanol concentration; however, its surrounding area is of gradually-increasing ethanol concentration, which shows that the burning diesel immediately ignites the ethanol in this area, and then diesel in a number of places burns and ignites the mixed ethanol. In addition, the spread of flame can also result in mixed ethanol combustion. The later the initial ethanol injection starts, the higher the concentration of ethanol in the ω combustion chamber will be, and the more ethanol will be burnt during the rapid combustion period. This is the reason that the initial heat release rate curve rises rapidly and the pressure increase rate is high. On the other hand, with the higher concentration of ethanol in the ω combustion chamber, the oxygen concentration will be reduced correspondingly. As a large number of oxygen in the ω combustion chamber is consumed in the initial period, the incomplete combustion of diesel injection in the later period increases, this is the reason that lower average temperature in the cylinder due to later initial ethanol injection in the post-combustion period.



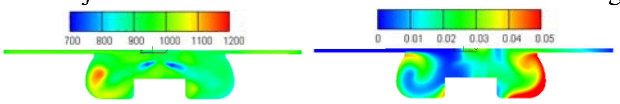
a) Temperature of ethanol initial injection at 240°CA Ethanol concentration during initial injection at 240°CA



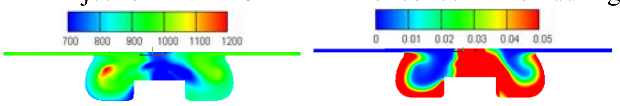
b) Temperature of ethanol initial injection at 260°CA Ethanol concentration during initial injection at 260°CA



c) Temperature of ethanol initial injection at 280°CA Ethanol concentration during initial injection at 280°CA



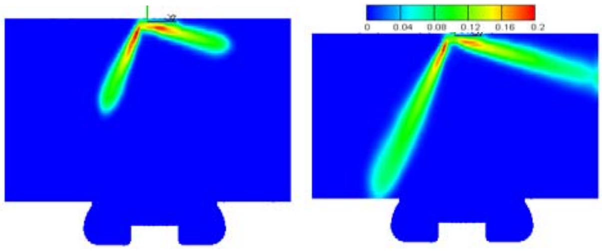
d) Temperature of ethanol initial injection at 300°CA Ethanol concentration during initial injection at 300°CA



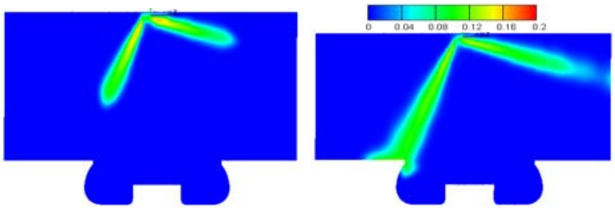
e) Temperature of initial injection at 319.4°CA Ethanol concentration during initial injection at 319.4°CA

Figure 6. Temperature distribution and ethanol concentration in the cylinder when the ignition starting point is 354°CA

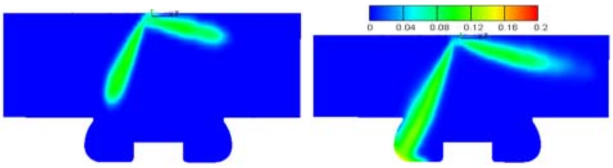
Figure 7 shows the ethanol component distribution at 10°CA and 20°CA after the ethanol injection (extracted from the section B where the ethanol spray is located in Fig. 1). As ethanol injection is carried out soon after the inlet valve is closed, such as 240°CA and 260°CA ethanol injection, there is a longer atomization time between the ethanol injection and combustion start. During injection, both the pressure and temperature and the density of the gas in the cylinder are lower, and the ethanol spray suffers the small resistance of the gas in the cylinder and it has strong penetrating capability. In addition, the piston is lower, most ethanol spray collides at the top of the cylinder wall and piston top ring surface, spray atomization time in the cylinder is longer, and atomization space is wider, as shown in Figure 7a and Figure 7b. After the injection delay, such as 280°CA and 300°CA ethanol injection, piston has moved upwards for a long distance, and the fuel spray with larger injection angle will enter the ω combustion chamber, as shown in Figure 7c and Figure 7d. In case of the initial ethanol injection at 319.4°CA, the fuel spray will be mainly concentrated in the ω combustion chamber. In this case, the cylinder pressure and temperature is higher than that in previous conditions. In addition, the gas density is high. Due to increasing impact of the cylinder gas on the ethanol spray, the penetration speed is reduced, the fuel spray particles become finer, and spray cone angle increases. Moreover, a strong vortex has been formed in the ω combustion chamber. As higher temperature in the cylinder is conducive to ethanol gasification, a lot of mixed ethanol with proper concentration is distributed in the ω combustion chamber. With burning of injected diesel subsequently, the mixed ethanol in the ω combustion chamber can be quickly and massively ignited, resulting in burning of more ethanol during the rapid combustion period. Therefore, in case of the initial ethanol injection at 319.4°CA, the combustion heat release rate and the pressure rise rate curve during the initial combustion period are the steepest, and the maximum combustion pressure, temperature, and NO concentrations are also the highest. However, in case of earlier initial ethanol injection, the mixed ethanol distribution space is wide, the ethanol wall interaction is mainly concentrated at the cylinder wall and piston ring top surface, and concentration of mixed ethanol in the ω combustion chamber is low. Therefore, after being ignited by the diesel, the mixed ethanol combustion will spread along with the flame propagation and the ethanol will gradually burn along with the diesel diffusion, thus the early heat release rate and the pressure rise rate is low.



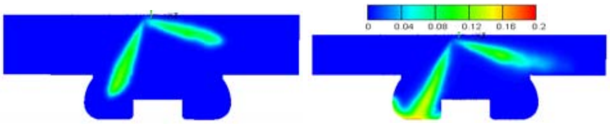
a) 10°CA after ethanol initial injection at 240°CA 20°CA after ethanol initial injection at 240°CA



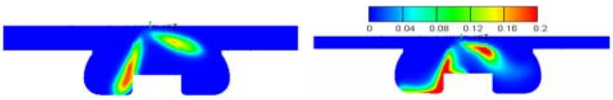
b) 10°CA after ethanol initial injection at 260°CA 20°CA after ethanol initial injection at 260°CA



c) 10°CA after ethanol initial injection at 280°CA 20°CA after ethanol initial injection at 280°CA



d) 10°CA after ethanol initial injection at 300°CA 20°CA after ethanol initial injection at 300°CA



e) 10°CA after ethanol initial injection at 319.4°CA 20°CA after ethanol initial injection at 319.4°CA

Figure 7. Ethanol component distribution 10°CA and 20°CA after the ethanol injection

5. Conclusion

Five conditions featured by the ethanol injection completion prior to the initial diesel injection are calculated and analyzed with the established 3D combustion model. The following conclusions can be drawn based on the installation position of fuel injectors of the tested engine and the injection angle of the holes:

(1) The later the ethanol injection, the higher the ethanol concentration in the ω combustion chamber, namely, in case of initial injection at 319.4°CA, the preliminary combustion heat release rate and the pressure rise rate will be the maximum, the combustion pressure will be the highest and the phase will be the headmost.

(2) In case of later initial ethanol injection, the average temperature in the cylinder during the initial combustion period will have a faster rise. In case of initial injection at 319.4°CA, the average temperature in the cylinder is the highest, followed by 240°CA ethanol injection. In the post-combustion stage, the earlier ethanol injection will result in the higher average temperature in the cylinder and the more complete fuel combustion.

(3) In case of initial injection at 319.4°CA, NO generation will be earlier and emission will be the maximum. The higher the average temperature in the cylinder, the higher the NO concentration will be.

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