Simulation Study of Injection Strategy on the Emission in Automotive Engine

Huanhuan Ren*, Guorui Jia, Dongchang Zhao, Chuan Chen, Rujie Yu, Peng Ge, Shaohui Liu
China Automotive Technology and Research Center, Tianjin, P. R. China, 300300

*Corresponding author e-mail: jiaguorui@catarc.ac.cn

Abstract. To realize the clean combustion in the automotive engine, multi-injection strategy with two kind of fuel has attracted the attention of technicians due to the flexibility to control the concentration and activity stratification of mixture in the engine cylinder. This paper shows the effect of various injection strategy of high-activity fuel on the emission. Results showed that adjusting multiple injections strategy had the ability to optimize the stratification of the mixture and to decrease the production of emission, such as NOx, Soot and UHC. The emissions, either soot or NOx will increase in the cases of large ratio at early or late injection at Multi-injection strategy.

1. Introduction
Increasingly stringent emission regulations drive the development of combustion technology of engines in traditional automobiles. Nowadays, the working range of clean combustion are widened by adjusting the inlet temperature, pressure and injection strategy [1].

The high volatility of gasoline fuel and variable valve is coupled to control the residual gas in cylinder. And the heating effect and low activity of exhaust gas are used to control the formation of emission [2-3]. Due to the low volatility, it is difficult for diesel fuel to achieve homogenous charge compression ignition in all conditions. For the same reason, the “wet wall” phenomenon are always found in the early injection strategy of diesel at low pressure, which will induce the formation of soot, while hydrocarbon emissions are formed because of the fuel dilution [4]. To eliminate the "wet wall" caused by long-term fuel injection, multiple injections are used to avoid long fuel penetration. Meanwhile, mixture concentration and activity stratification are achieved by setting the injection ratio [5]. Liszt, For example, developed a homogeneous compression ignition system with spark plug ignition and compression ignition using multiple injection technology.

In order to explore the influence of multiple injection on emissions, one combustion model with new mechanism of multi-component fuel substitutes for gasoline and diesel was constructed in this paper, the effects of multiple injection strategy on the formation and consumption of radical, molecule evaluation and emissions are analyzed by coupling 3D-CFD fluid code.

2. Construction of simulation model
The chemical kinetics mechanism model of gasoline and diesel surrogates were coupled with KIVA-CFD. The combustion mechanism of gasoline and diesel include n-heptane, toluene, CHX, DIB, iso-
octane, NOX, and PAH. The sub-model used in CFD is listed at Table 1. According to the previous experiment and simulation result [6], the boundary conditions for simulation of the three-injection strategy are shown in Table 2.

| Application object | Sub-model                        |
|---------------------|----------------------------------|
| Spray model         | KH-RT instability                |
| Evaporation model   | DMC (Discrete Multi-component fuel)|
| Turbulence model    | Renormalized κ-ε model           |
| Combustion model    | SpeedChem                        |
| Droplet breakage    | ROI (Radius of influence)        |
| Spray outlet        | Gas-jet model                    |

Table 2. Computational boundary conditions for the three-injection strategy

| Comparison case | SOI1 | SOI2 | SOI3 | SOI4 |
|-----------------|------|------|------|------|
| Gasoline injection (mg/cycle) | 30   | 30   | 30   | 30   |
| Diesel injection (mg/cycle)    | 20   | 20   | 20   | 20   |
| Start of Injection (SOI)       | -35,-20,-5°CA ATDC                |
| injection ratio (%)            | 25,50,25                          |
|                               | 50,25,50                          |
|                               | 33,33,33                          |

3. Results and Discussion

As shown in Figure 1, it is the concentration of important species about emissions in the cylinder under four injection strategies. Figure 1(a) and (b) show that the production of H2O2 in SOI3 is the highest (up to 1.4×10^{-3}). Meanwhile, the peak concentration of OH mole fraction is the highest and it is produced by subsequent decomposition of H2O2. However, the H2O2 produced by SOI2 was relatively late and the peak concentration was low (1.1×10^{-3}), and the concentration of OH radical produced by subsequent decomposition was relatively low (2.6×10^{-4}). It shows that there are more active free radicals in the cylinder. These radicals are conducive to the dehydrogenation and oxidation of fuel molecules, which means they are beneficial for the complete combustion of fuel.

![Figure 1](image_url)
Meanwhile, the concentration profiles of CH2O and CO are compared in Figure 1, which are more important and representative species in the high temperature stage. As shown in Fig. 1(c) and (d), the peak concentration of CH2O produced by SOI3 is the highest (the mole fraction concentration is $1.5 \times 10^{-3}$). However, the proportion of consumption is larger in the subsequent, and the residual concentration of CO in the cylinder is relatively low relatively (the mole fraction of CO is $4.1 \times 10^{-3}$).

The concentration slices of OH and CO radicals in cylinder are showed in Figure2 and 3. The distribution of OH radicals in SOI3 and SOI4 is mostly concentrated in the middle of piston dent, which is beneficial for the oxidation of CO at the bottom of the pit. In contrast, the OH distribution of SOI2 is more inclined to the upper part of piston pit. The timing of OH formation is relatively late, and the area is narrow.

In Figure 3, parts of CO remain at the bottom of piston pit in combustion chamber and the phenomenon is obvious in SOI2 case. However, there are CO residue at the bottom of the pit at the later stage of combustion because of large production of OH radicals at the beginning. Another important result is that the flame of SOI1,3,4 diffuse into the slit area of the combustion chamber. It is beneficial for the combustion and consumption of low active fuel mixture in the slit region to decrease the CH2O, CO and UHC content in the late phase of combustion.

![Figure 2](image2.png)  
Figure 2. The concentration distribution of OH radicals in cylinder

![Figure 3](image3.png)  
Figure 3. The concentration distribution of CO radicals in cylinder
Figure 4 shows the concentration profile of Soot and NOx in the cylinder. From the Soot concentration curve shown in Fig.4(a), it is known that the generation sequence of Soot in the cylinder is SOI1>SOI4>SOI3>SOI2.

According to the analysis, the high equivalence ratio region of SOI1 is relatively wide because of its weak concentration stratification, and the fuel concentration region is located in the high temperature region with low temperature gradient. Therefore, the concentration of Soot is the highest at 5°CA ATDC (1.39×10⁻³).

While the concentration peak value of Soot in SOI2 is the lowest (8.1×10⁻⁴) due to the incomplete combustion, low temperature and low equivalence ratio in delamination. And the results show more intuitionistic about the soot distribution in Figure5.

![Figure 4](image1.png)

**Figure 4.** The mole fraction profile of Soot, NOx, CH2O and CO in cylinder

It is shown that the order of NOx emission is SOI3>SOI4>SOI1>SOI2 in Figure 4(b). The peak value of NOx emission is high in SOI3 and SOI4 due to the relatively high temperature (SOI3: 9.4×10⁻⁴; SOI4: 8.8×10⁻⁴). While the peak value (4.9×10⁻³) of NOx is low due to the maximum and average temperatures of SOI1 is relatively low. For SOI2 in Figure4, it is the lowest peak value and production of NOx (2.1×10⁻³) because of incomplete combustion and low temperature showed in Figure5.

![Figure 5](image2.png)

**Figure 5.** The concentration distribution of Soot and NOx in cylinder
4. Conclusion
The effects of injection strategy on the formation of emission are analyzed, the results are concluded as followed:

1. In the early injection with more mass, the stratification with moderate concentration gradient is beneficial for soot emission reduction. While it will produce more NOx due to the high temperature.

2. The more injection mass at later injection time, the worse effect of concentration and active stratification in cylinder, it will produce the more soot emission. The late ignition of SOI2 leads to the incomplete combustion and the high emission of unburned hydrocarbon.

3. The coupling control of active stratification and concentration stratification of the mixture can be realized by adjusting the injection strategy of high active fuel to affect the final emission.

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