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Effects of Intake Manifold Water Injection on Combustion and Emissions of Diesel Engine

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Abstract

Intake manifold water injection (IMWI) is an effective way to control combustion temperature and NOx emission for diesel engines. The various effects of IMWI on diesel combustion and emissions reflect on the dilution effect, thermal effect and chemical effect. However, researchers have paid little attention to investigate the three effects. In this study, the dilution, thermal and chemical effects of IMWI on the combustion and emissions characteristics of a four-stroke, direct injection as well as turbocharged diesel engine are investigated by CFD simulation. The results indicate that IMWI reduces the in-cylinder mean pressure and temperature, and the ignition delay becomes longer. IMWI leads to a remarkable decrease of NOx and Soot emissions. Comparing to the thermal effect and chemical effect, the dilution effect of IMWI on engine combustion and emissions plays a dominant role.

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Keywords: Diesel engine; Intake manifold water injection; Emissions; Dilution effect

1. Introduction

IMWI is an effective way to control combustion temperature and NOx emission for diesel engines, which is widely used on large marine engines[1]. This method increases the ignition delay and peak heat release rate, whereas in-cylinder temperature and NOx emission drop. The decrease in in-cylinder temperature and NOx emission is the result of various effects of IMWI: dilution effect (decrease of inlet oxygen concentration), thermal effect (high latent heat of vaporization and specific heat capacity of injected water) and chemical effect. The chemical effect has little effect on engine combustion and emissions. This three effects on combustion and emissions production are difficult to distinguish, and thus the influence of IMWI on engine combustion and exhaust emissions is not perfectly understood. Most researchers considered the decrease in in-cylinder temperature and NOx emission were mainly attributed to the high latent heat of vaporization and specific heat capacity of injected water[2,3]. However, Xavier

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Tauzia et al found the dilution effect affected engine combustion and emissions more[4]. In this study, the dilution, thermal and chemical effects of IMWI on the combustion and emissions characteristics are investigated by CFD simulation.

2. Computational procedure

2.1 computational model and validation

Table.1 Specifications of the engine

Type	Value	Type	Value
Bore×stroke/mm	132×145	Compression ratio	17:1
Connecting rod length/mm	262	Rated speed × power /($r\cdot min^{-1}$×kW)	2100×300

Simulations were conducted on a four-stroke, direct injection and turbocharged diesel engine. Table 1 shows the engine specifications. The CFD code AVL FIRE was utilized to show the complex physical and chemical processes involved in diesel spray combustion process. The submodels used in the calculation are showed in Table 2

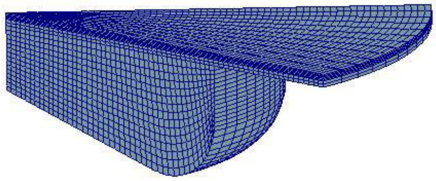
Table 2. Submodels used in the calculation

Type	Model	Type	Model
Turbulence model	k - zeta - f	Auto ignition model	Table
Wall interaction model	Walljet1	Combustion model	ECFM-3Z
Evaporation model	Dukovicz	NOx model	Extended Zeldovich mechanism
Breakup model	Wave	Soot model	Kennedy Hiroyasu Magnussen

Fig 1a shows the engine combustion chamber computational mesh. To reduce the computation time, only a sector of 45° was used in the simulation with single injection in the 8-hole injector. The computations are started at the time of intake valve closure (IVC=-141°, ATDC), and ended at the time of exhaust valve open (EVO=123°, ATDC). The computational time step is 0.2°CA in the spray and combustion process, and other computational time step is 0.5°CA. The in-cylinder mean pressure and temperature at beginning of the calculation are 0.2209 MPa and 333K. The simulations are at constant engine speed (2100 $r\cdot min^{-1}$), constant cycle fuel injection quantity (138.7 mg/st). The initial swirl ratio is 0.7. The surface temperature of piston, cylinder head and linear are estimated as 593, 540, and 409K.

Fig 1b shows the comparison of in-cylinder pressure between experiment and simulation. The calculated in-cylinder pressures agree well with the measured results. The difference of peak in-cylinder pressure between experiment and simulation is 2.44%. With the comparison, it can be concluded that the selected computational model is reasonable.

2.2. Computational scheme



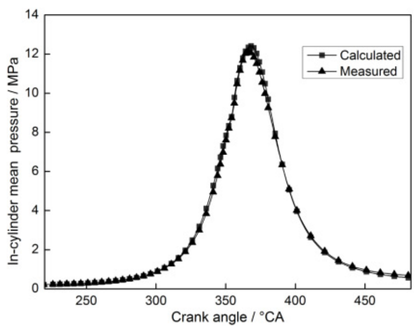


Fig.1. (a) computational mesh of the combustion chamber; (b) comparison of measured and simulated in-cylinder pressure

The computational scheme consists of two parts: 1) The nitrogen concentration in the inlet charge is constant, the intake oxygen is replaced by water at a temperature of 298K to simulate the comprehensive effect of dilution, thermal and chemical effects of IMWI, and the intake temperature reduces with water injection. 2) The oxygen concentration is equal to that of the previous part, the intake oxygen is replaced by nitrogen to simulate the dilution effect of IMWI, and the intake temperature is constant at 333K. With the comparison of the above results, the thermal and chemical effects of IMWI are obtained.

3 Results and discussion

3.1 combustion characteristics analysis

Fig 2 shows the variation of in-cylinder mean pressure and temperature under different composition in the inlet charge. When the intake oxygen is replaced by water or nitrogen, the in-cylinder pressure and temperature reduces. The decrease in-cylinder pressure and temperature with oxygen replaced by water is larger than that of same mass fraction oxygen replaced by nitrogen. The dilution effect plays a dominant role on the decrease of in-cylinder pressure and temperature.

Fig 3a describes the variation of heat release rate under 3% and 6% mass fraction oxygen replaced in the inlet charge. When the intake oxygen is replaced by water or nitrogen, the ignition delay becomes longer. With the intake oxygen replaced, the heat release rate in early diffusion combustion phase is lower than that of the original diesel engine, but the heat release rate in late diffusion combustion phase is larger than that of the original diesel engine. Because of the decrease of intake oxygen concentration, fuel can't get enough oxygen to form the combustible mixture, which leads to the decrease of burning rate in the early diffusion combustion phase. Meanwhile as the decrease of burning rate, the combustion duration increases, which leads to the increase of heat release rate in the late diffusion combustion phase. What's more, with the increase mass fraction of oxygen replaced, the trend of this difference become larger.

With the intake oxygen replaced by water or nitrogen, the difference of heat release rate between them is the premixed combustion phase. The ignition delay and peak heat release rate of oxygen replaced by water is larger than that of oxygen replaced by nitrogen due to the thermal effect of IMWI. In addition, the heat release rate in the diffusion combustion phase between them are consistent, which indicates that the heat release rate in diffusion combustion phase is mainly depended on the in-cylinder oxygen concentration, and the thermal and chemical effect of water have little influence on it.

3.2 Emissions characteristic analysis

Fig 3b shows the change rate of NOx and soot emissions under different composition in the inlet

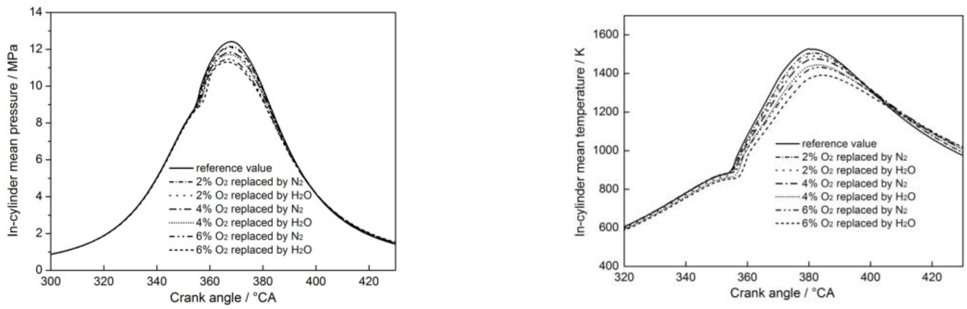


Fig.2.(a) In-cylinder mean pressure under different composition in the inlet charge; (b) In-cylinder mean temperature under different composition in the inlet charge

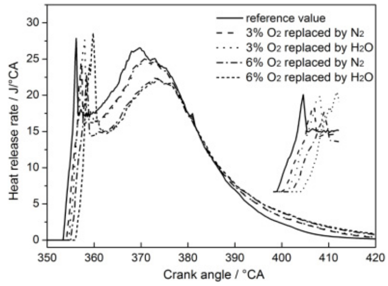
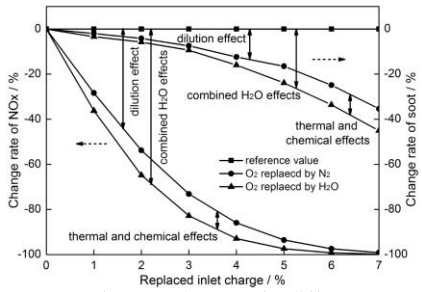


Fig.3.(a) heat release rate under different composition in the inlet charge



(b) change rate of NOx and soot under different composition in the inlet charge

charge. When the oxygen is replaced by water, the NOx emission decreases significantly, which is the comprehensive effect of dilution, thermal and chemical effects of IMWI. When the oxygen is replaced by nitrogen, the NOx emission also decreases significantly, which is due to the dilution effect. But the decline is smaller than that of intake oxygen replaced by water. The difference between two curves represents the thermal and chemical effect on NOx emission. The dilution effect of IMWI on NOx emission is much larger than other effects, which is in good agreement with Xavier Tauzia et al[4].

With the intake oxygen replaced by water or nitrogen, the soot emission reduces, which is due to these simulations being in part load condition. With no intake oxygen replaced, the air fuel ratio is 32.175, which means that the in-cylinder oxygen is sufficient, so the soot generation is mainly depended on in-cylinder combustion temperature. Thus, as the increase of intake oxygen replaced, in-cylinder temperature decreases, and the soot emission decreases. However, when the load condition changes, the effect of intake oxygen concentration on soot emission are different[5]. From Fig 3b, it's also observed that the dilution effect on Soot emission is much larger than other effects of IMWI. In addition, with the increase mass fraction of oxygen replaced, the thermal and chemical effects on NOx emission increases.

Conclusions

1. IMWI reduces in-cylinder mean pressure and temperature, and the dilution effect of IMWI plays a dominant role on the decrease of in-cylinder mean pressure and temperature.

2. IMWI decreases the burning rate, and increases the combustion duration. The thermal and chemical effects of IMWI mainly affect the premixed combustion phase. The heat release rate in diffusion combustion phase is mainly depended on the dilution effect of IMWI, and the thermal and chemical effects have little influence on it.

3. In part load condition, IMWI reduces in-cylinder combustion temperature, which leads to the decrease of NOx and soot emissions. The dilution effect of IMWI plays a dominant role on reduce exhaust emissions for diesel engines.

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Biography

Xiao-kang Ma is doctoral student at the Department of School of Mechanical and Vehicle Engineering, Beijing Institute of Technology, China. He is actively involved in research activities in the field of evaporation and combustion of biofuel for diesel engines.