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NUMERICAL STUDY ON EFFECTS OF CALIBER RATIO AND CALIBER-DEPTH RATIO ON COMBUSTION AND EMISSION CHARACTERISTICS IN A DIESEL ENGINE

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ABSTRACT

Caliber ratio and caliber-depth ratio as two important structural parameters for the combustion chamber design directly affect the in-cylinder air motion and the fuel-air mixture distribution, which further influence the combustion process. This paper is presented to study the effects of these two important parameters on combustion and emission characteristics of a diesel engine. Results showed that increasing the caliber ratio increased ISFC (Indicate specific fuel consumption) value and soot emissions, while decreased the NOx emissions. A first decrease then increase trends were obtained for both ISFC and soot emissions as the increase of the caliber-depth ratio and the turning points were all located near the ratio of 4.0, which was just opposite to NOx emissions variations. In additions, for both caliber ratio and caliber-depth ratio variations, the proportions of NOx and soot emissions in the near wall region and central region were the greatest, respectively, and mainly contributed to the variations of NOx and soot emissions.

Keywords: diesel engine, caliber ratio, caliber-depth ratio, combustion characteristic, emission characteristic

NONMENCLATURE

Abbreviations	
BTDC	Before Top Dead Center
ATDC	After Top Dead Center
TDC	Top Dead Center
CA10/CA50/ CA90	Crank angle when the accumulated heat release reached 10%/50%/90% of the total heat release
ISFC	Indicate specific fuel consumption
TKE	Turbulence kinetic energy
NOx	Nitric oxides

1. INTRODUCTION

Due to the advantages of superior fuel economy, durability, reliability, and high specific power output compared to gasoline engines, diesel engines have been widely used not only for heavy-duty vehicles such as trucks, construction machine and generators but also for light-duty ones including passenger's cars [1-2]. The geometry of the combustion chamber directly affect the in-cylinder fuel-air mixture formation, as well as the combustion and emission characteristics. Re-entrant combustion chamber has been widely used in the high-speed diesel engines due to the advantage on increasing the in-cylinder turbulence intensity which can promote the fuel-air mixing then improve the performance of combustion and emission [3-4].

Ge et al. [5] investigated the effects of open chamber and re-entrant chamber on the diesel performance. Results showed that lower soot emissions and fuel consumption could be obtained by using the re-entrant chamber with smaller diameter and higher swirl ratio. In additions, with the increase of the load, the optimum value of the chamber diameter also increased linearly. Styron et al. [6] compared the in-cylinder fuel-air mixture distribution of three kinds of re-entrant chamber including chamfered, wide and deep re-entrant chamber. Results showed that the in-cylinder fuel-air mixture distributed more homogenous by using chamfered re-entrant chamber. And due to the lean fuel-air mixture formed in the near wall region, the combustion temperature in this region also decreased which reduced the heat transfer loss. However, when using the wide re-entrant chamber, over-rich fuel-air mixture formed in the piston head region resulting in excessive soot emissions. Li et al. [7] investigated the variations of the combustion and emission characteristics according to different diameter and

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shallow depth of the combustion chamber. Results showed that the decrease of the chamber diameter was beneficial to improve the fuel-air mixture, and chamber with smaller shallow depth showed a better engine performance under part load. The study of Jafarmadar et al. [8] showed that the smaller shallow depth and bigger diameter of the chamber enhanced the in-cylinder squish motion and swirl motion respectively, which all decreased the soot emissions.

The effects of caliber ratio and caliber-depth ratio on the combustion and emission characteristics have been numerically investigated. Besides, the calculation grid has been divided into three regions, and the NOx and soot emissions in each region have also been discussed.

2. MODELING METHODOLOGY

2.1 Engine specifications and operating conditions

The specifications of the engine used in the test are shown in Table 1. It is a 4-cylinder inline and naturally aspirated diesel engine, and the operating condition in this paper has been fixed at 2000 rpm with 100% load.

Table 1. Engine specifications

Parameters	Value
Bore × stroke	100 × 105 mm
Connecting-rod length	175mm
Compression ratio	17.5:1
Swirl Ratio	3.4
Type of combustion chamber	ω type
Spray angle	160-degree
Holes no./nozzle diam.	6/0.24 mm
Spray cone angle	8-degree

2.2 Definition and selection of the caliber ratio and caliber-depth ratio

The caliber ratio is defined as the ratio of inner chamber diameter (Di) and outer chamber diameter (Do), and the caliber-depth ratio is defined as the ratio of inner chamber diameter (Di) to the shallow depth (H). In this paper, the caliber ratio varied from 7.6% to 13.6%, with caliber-depth ratio (3.2) and compression ratio (17.5) unchanged. And the caliber-depth ratio varied from 2.1 to 4.8, with caliber ratio (7.6%) and compression ratio (17.5) unchanged, as shown in Fig.1.

2.3 Calculation grid and initial conditions

The calculation grid employed in this study consisted of a 1/6 sector model of a single fuel spray based on assuming cyclic symmetry, and the calculations were carried out for a closed system, starting from closing of the intake valve at 132° BTDC to opening of the exhaust valve at 114° ATDC. The initial conditions including charging pressure, charging temperature, piston head temperature, cylinder head temperature and cylinder wall temperature were set as 20.1kPa, 340K, 550K, 550K and 475K, respectively.

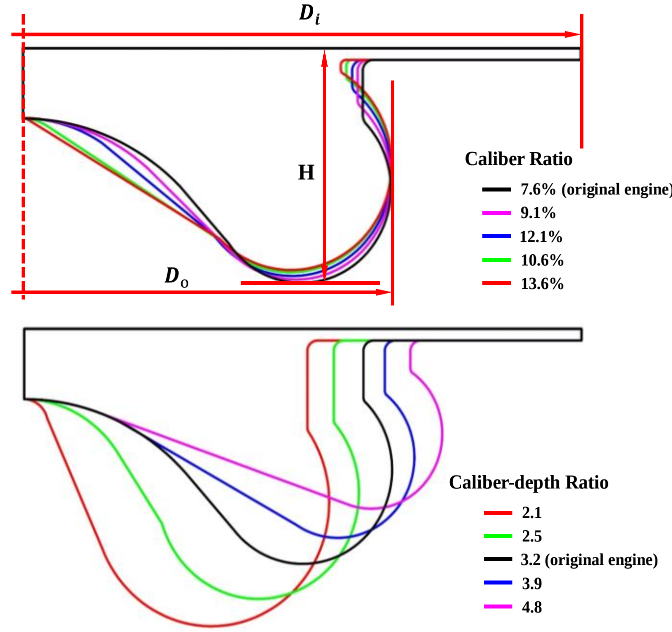

Fig.1. Definition and variations of caliber ratio and caliber-depth ratio

2.4 Sub-models

The sub-models including turbulence, spray breakup and atomization, spray-wall impingement, wall-film, combustion and emission models are listed in Table 2.

Table 2. Seclection of the Sub-models

Sub-models	Name
Turbulence	k-zeta-f
Atomization/breakup	Dukowicz/WAVE
Wall impinging	Moudo/Sommerfeld
Wall-film evaporation/entrainment	Combined/ Schadel-Hanratty
Combustion	ECFM -3Z
NOx formation	Extended Zeldovich
Soot formation	Kennedy/Hiroyasu/Magnussen

2.5 Model validation

The goal of numerical simulation is to reproduce the cylinder pressure and the exhaust gas emission characteristics during the test as accurately as possible. Fig.2 compares experimental and calculated results of cylinder pressures and engine-out NOx and soot emissions. The calculated results shown in these figures capture the features of the experimental results fairly well.

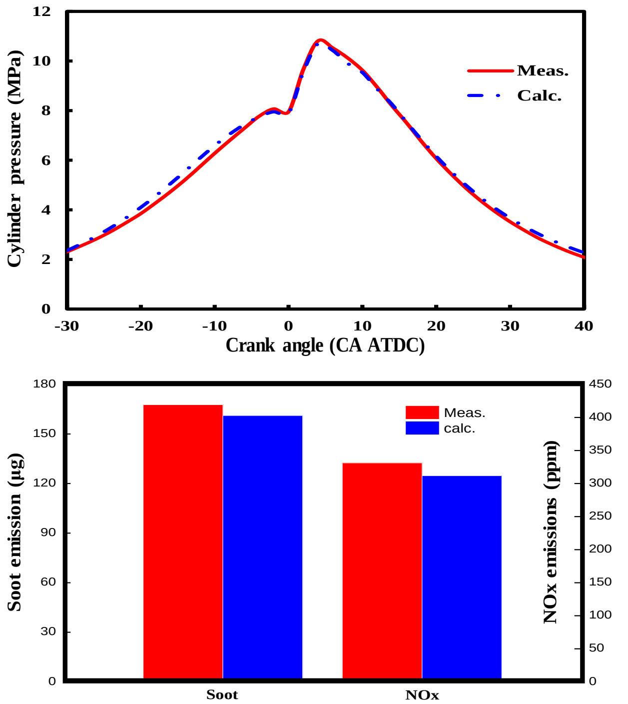

Fig.2 Comparison of calc. and meas. cylinder pressureand emission characteristics

3. RESULTS AND DISCUSSION

3.1 Combustion characteristics

Fig.3 summarizes the effects of varying the caliber ratio and caliber-depth ratio on the ISFC, which showed an increase trend of ISFC value variation according to the increase of the caliber ratio while a first decrease then increase trend according to the caliber-depth ratio variation.

To explain this phenomenon, we assessed several parameters related to the heat release timing, such as CA50, and combustion duration (crank angles from CA10 to CA90) as well as those related to the quantity of heat released, such as maximum in-cylinder pressure (P_{max}) and temperature (T_{max}).

As shown in Fig.3(a), as the caliber ratio increased, the CA50 retarded and the combustion duration prolonged resulting in a weaker heat release near TDC, which led the increase of ISFC value. The CA50 was firstly advanced then retarded as the increase of the caliber-depth ratio and a first decrease then increase trend was obtained for the combustion duration variation as shown in Fig.3(b). These two effects resulted in a lowest ISFC value when the ratio was near 4.0.

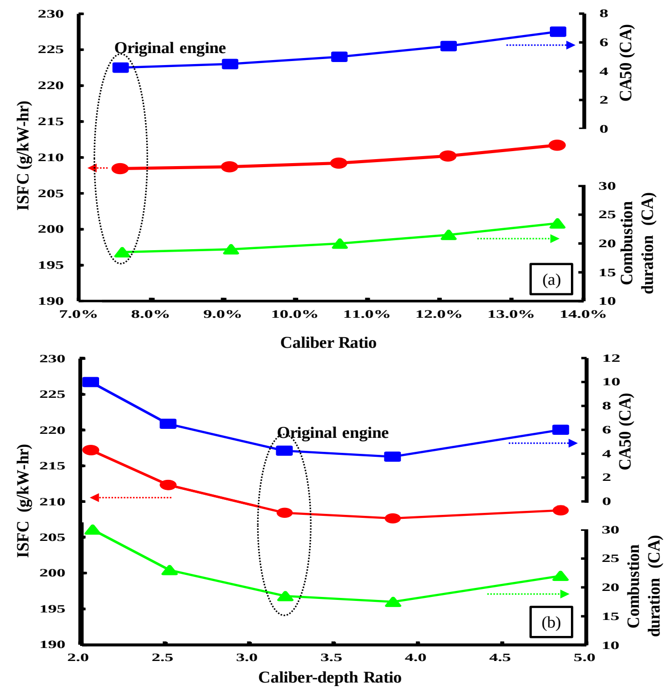

Fig.3 Effects of caliber ratio (a) and caliber-depth ratio (b) on combustion characteristics

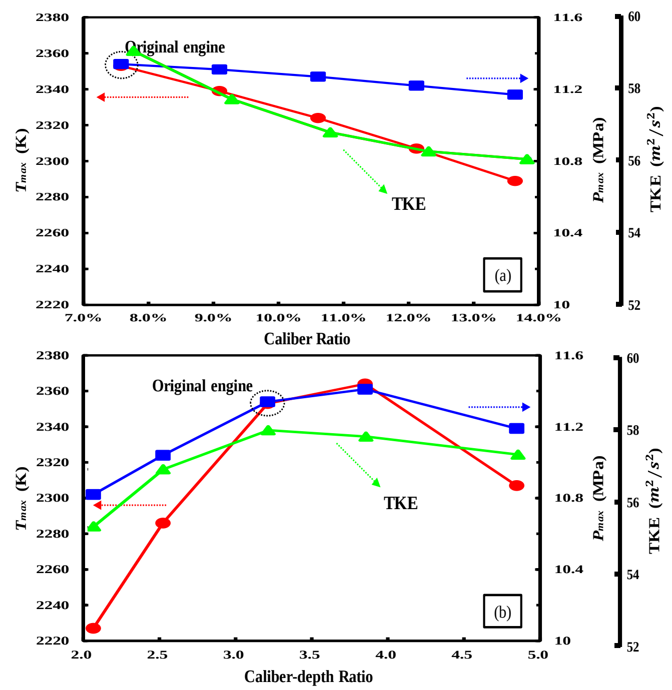

Fig.4 Effects of caliber ratio (a) and caliber-depth ratio (b) on TKE, P_{max} and T_{max}

The difference of the combustion characteristics between the variations of caliber ratio and caliber-depth ratio was mainly attributed to the in-cylinder turbulence intensity. As shown in Fig.4(a), the maximum value of the in-cylinder turbulence kinetic energy decreased as the increase of the caliber ratio. It caused the weaker fuel-air mixing strength resulting in a slower heat release process and a retard of CA50. The variations of CA50 and combustion duration of different caliber-depth ratio could also be explained by the turbulence intensity reason as shown in Fig.4(b).

Because of the accumulated heat release was almost the same for either caliber ration or caliber-depth ratio, the shorter combustion duration meant higher heat release rate resulting in higher maximum values of in-cylinder pressure P_{max} and temperature T_{max} as shown in Fig.4. Both P_{max} and T_{max} decreased as the increase of caliber ratio and the greatest values of P_{max} and T_{max} were obtained when the caliber-depth ratio was near 4.0.

3.2 Emission characteristics

Fig.5(a) plots the emission characteristics as functions of the caliber ratio. As the caliber ratio increased, the NOx emissions decreased while the decreasing rate slowed down. This effect was mainly ascribed to the reduction of the in-cylinder temperature. While, the prolongation of combustion duration was adverse for the decrease of NOx emission resulting in the slow-down of the decreasing rate.

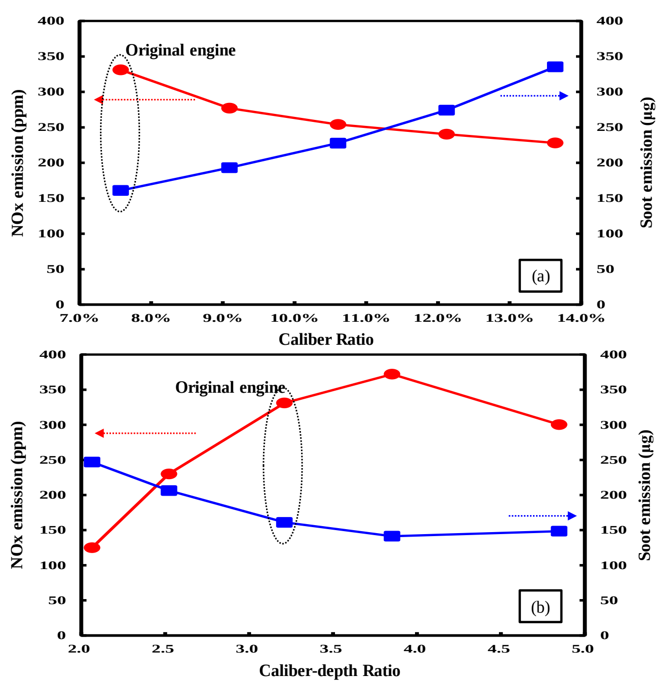

Fig.5 Effects of caliber ratio (a) and caliber-depth ratio (b) on emission characteristics

The soot emission increased with the increase of the caliber ratio and the increasing rate also increased. This was attribute to the existence of the fuel-rich zones, and the proportion of the over-rich region was increased with the increase of the caliber ratio (as shown in Fig.6 (a)) due to the weaker turbulence intensity previously mentioned. In addition, the reduction of the in-cylinder temperature was also against to the soot oxidation resulting in the increase of the increasing rate.

Fig.5(b) shows the emission characteristics with the variations of the caliber-depth ratio. Increasing the caliber-depth ratio, the NOx emission increased firstly but the increasing rate slowed down gradually then decreased after the caliber-depth ratio of 4.0, which was the same as the variation trend of the in-cylinder temperature. The soot emission decreased firstly and obtained the minimum value when the caliber-depth ratio increased to 4.0. This could be also explained by the reasons of in-cylinder fuel-air distribution as shown in Fig.6 (b) and the in-cylinder temperature.

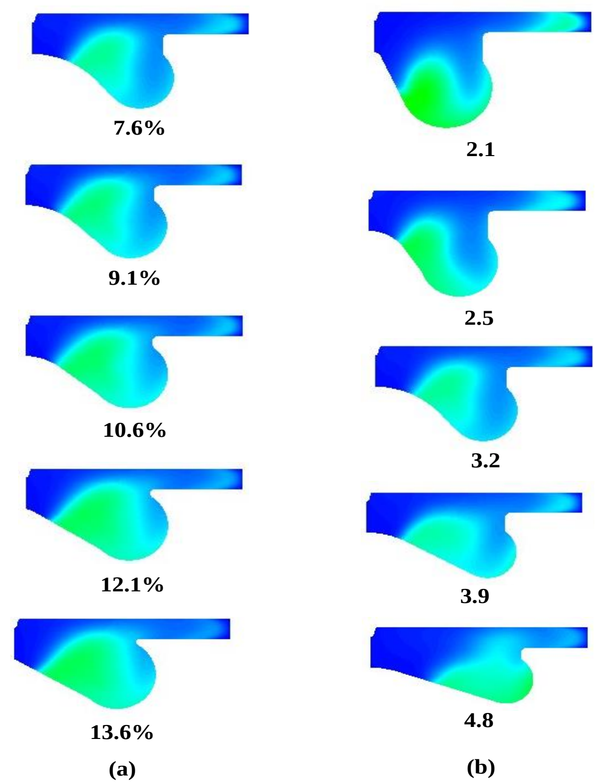

Fig.6 Effects of caliber ratio (a) and caliber-depth ratio (b) on in-cylinder fuel-air distribution (20°ATD)

3.3 Detailed analyses by using divided region

To further elucidate the effects of the caliber ratio and caliber-depth ratio on emission characteristics, the in-cylinder zone is divided into three different regions as shown in Fig.7. These are defined as the combustion chamber, central and near wall wetting regions

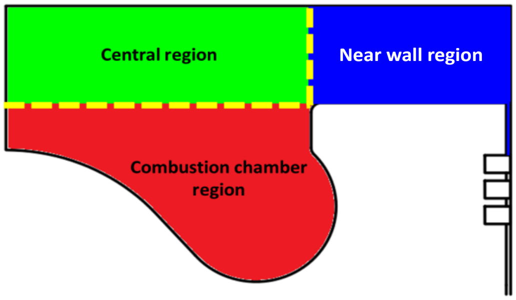

Fig.7 Schematic diagram of the region definition

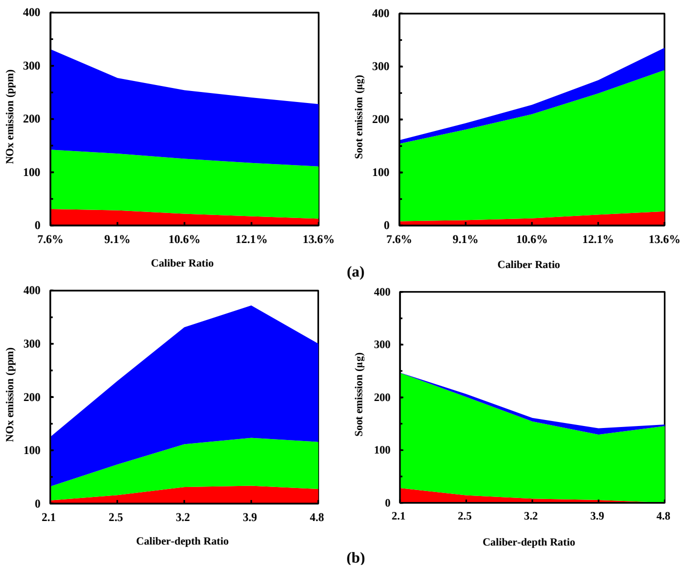

Fig.8 Effects of caliber ratio (a) and caliber-depth ratio (b) on NOx and soot emissions in each region (red: combustion chamber region, green: central region, blue: near wall region)

Fig.8 (a) summarizes the effects of the caliber ratio on NOx and soot emissions in each region. The near wall region evidently made the greatest contribution to the NOx emissions, followed by the central and combustion chamber regions. Increasing the caliber ratio continually lowered the NOx emissions in each region, while the NOx emissions in the near wall region declined most steeply. These results indicated that variations in the overall NOx emissions upon applying different caliber ratio could be attributed to changes in the NOx emissions from the near wall regions. It was evident that the central region made the greatest contribution to the soot emissions. Increasing the caliber ratio primarily increased the soot emissions in the central region. In additions, the near wall region and central region also made the greatest contribution to the NOx and soot emissions varying the caliber-depth ratio, respectively, as shown in Fig.8 (b).

4. CONCLUSION

Numerical investigations were carried out to analyze the effects of caliber ratio and caliber-depth ratio on the combustion and emission characteristics of a diesel engine, and the following conclusions were derived.

Increasing the caliber ratio increased ISFC value, while a first decrease then increase trend was obtained as the increase of the caliber-depth ratio which could be explained by the variations of CA50 and combustion duration.

The variations trends of NOx and soot emissions showed a trade-off relationship. With the increase of caliber ratio, NOx emissions decreased while soot emissions increased. In additions, the variations of NOx emissions showed a first increasing then decreasing trend, which was opposite to soot emissions, and the turning points were all located near the caliber-depth ratio of 4.0. In additions, for both caliber ratio and caliber-depth ratio variations, the proportions of NOx and soot emissions in the near wall region and central region were the greatest, respectively, and mainly contributed to the variations of NOx and soot emissions.

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