Experimental study on the combustion, emissions and fuel consumption of elliptical nozzle diesel engine

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ABSTRACT

A series of experiments were carried out to investigate the combustion, emissions characteristics and fuel consumption of a diesel engine equipped with elliptical nozzle. The elliptical holes, which were made with an aspect ratio of 1.5, have a similar flow area as that of the references. In-cylinder pressure, exhaust emissions and fuel consumption were measured with varied fuel injection timing under a constant speed and different loads. The elliptical nozzles are characterized by shorter ignition delays, lower maximum rates of heat release and in-cylinder average temperature, and longer combustion durations. The NOx emission of the ICE with an elliptical nozzle is lower and while Soot emission higher. Under variable fuel injection timing, the NOx-Soot trade-off are affected by the nozzle shape. A substantial improvement in the fuel consumption-NOx emission trade-off is obtained for elliptic nozzles at three different loads. In current nozzle and injection strategy, employing moderate earlier injection coupled with elliptical nozzle could simultaneously improve the fuel consumption and emission performance of diesel engine.

KEY WORDS: Diesel engine; Elliptical nozzle; Combustion; Emissions; Fuel consumption

1. Introduction

The fuel injection and atomization performance and the matching with the air flow in cylinder directly determine the air-fuel mixing quality of the diesel engine. It's the key to optimize the combustion process, which has an importance influence on reducing pollutant emission and improving thermal efficiency of diesel engine. Improving the fuel atomization quality and intensifying the air-fuel mixing process by optimizing the fuel injection system and injection strategy are adopted by many scholars[1],[2,3].

In the theoretical study of spray and atomization, people gradually realized that the geometry of nozzle orifice has an important influence on the initial disturbance of spray, and scholars began to pay attention to the influence of jet orifice shape on fuel spray performance[4,5].The preliminary study shows that typical non-circular sprays such as ellipse, triangle and rectangle will undergo axis-switching phenomenon during the injection progress, with strong air entrainment effect, which is helpful to increase the spray and atomization quality. Furthermore, as compared with the traditional circular nozzle, the non-circular orifice can improve the atomization quality of fuel and air mixing process of diesel engine at the same injection pressure, which has the potential to get high thermal efficiency and combustion performance[6,7]. Because the non-circular nozzle has the potential to improve the quality of fuel atomization. scholars have conducted some beneficial exploration on non-circular nozzle inner flow and spray characteristics.

Molina et al. [8]conducted a simulation calculation of the cavitation inside the elliptical diesel nozzle. They found that the cavitation intensity, the effective velocity, and the discharge coefficient for the elliptical orifice are always higher than that of the circular diesel nozzle, which indicated that the application with the elliptical nozzle has potential ability to increase the fuel and air mixture quality. Yu et al.[9] reported the influence of the orifice shapes on the distribution of the cavitation inside the orifice, and it was found that the vapor phase fraction inside the elliptical orifice was smaller than that inside the circular orifice, and the cavitation area inside the elliptical orifice was mainly distributed on the major axis, while the cavitation inside the circular orifice was evenly distributed on the wall surface of the orifice.

Wang et al. [10]investigated the liquid jet breakup of rectangular and triangular orifices means of the shadow method under low pressures (0.48MPa). he Found that the triangular orifice had the most obvious effect on increasing jet breakup speed, and had the shortest breakup-length. Amini et al. [11] investigated the effect of the orifice shapes on the jet breakup process. The results show that the jet breakup length decreases gradually with the increase of the aspect ratio of the elliptical orifice. Rajesh et al. [12]found that the surface wave length of elliptical orifice was the largest under the condition of same jet velocity, and the surface wave length of circular was larger than square orifice. Farvardin et al.[13] [1]conducted a numerical study on comparing the axis-switching and breakup process of circular and elliptical holes, they found that the elliptical jet breakup faster and the elliptical jet breakup length was shorter. Yu et al.[14] [2]also studied the axis-switching and jet breakup behaviors with the application of elliptical nozzle by using Large Eddy Simulation method. The results show that compared with circular orifice, the central line velocity of the elliptic orifice spray is always smaller and the liquid column length of elliptic spray decreases. Kasyap et al.[15] found that breakup length of jet from elliptical orifice was shorter than the corresponding circular orifice, and the number of axis-switching increased with the increase of Reynolds number. Morad et al. [16]reported the spray breakup characteristics of the elliptical nozzle with different aspect ratios and a circular nozzle under the condition of low-speed cross flow. The results showed that the penetration distance of spray jet with elliptic orifices is smaller than that of the circular orifices, and different spray penetration can be obtained by changing the aspect ratio of elliptical orifice.

Ku et al. [17] investigated the atomization characteristics of a circular nozzle and elliptical nozzles of small diameter under high injection pressure, which has a hydraulic flip condition for the nozzle internal flow structure. They found that the disintegration characteristics of the liquid jet from the elliptical nozzle was different from those from the circular nozzle. Hong et al. [18] explored the internal cavitation of the circular and elliptical orifice and its influence on spray and atomization behaviors through experimental test. The results indicated that the intensity of cavitation was more intense at the outlet of the elliptical orifice, leading to a larger spray cone angle of the elliptical orifice. Kim et al.[19] reported the spray characteristics of elliptical and circular holes through experimental method under low injection pressures. They found that compared with circular spray, the spray cone angle of elliptical spray became larger while the elliptical spray penetration is shorter than the circular nozzle. Sharma P et al.[20] compared the atomization performance parameters of circular, elliptical, triangular, and rectangular orifices under the injection pressure of 100MPa, found that the spray cone angle and the projected aera of injection fuel spray from elliptic were the largest. Yu et al. [21,22]also studied the spray characteristics and fuel–air mixing quality of elliptical nozzle and circular nozzle under different injection pressures. They found that the spray tip penetration of elliptical nozzle is shorter than circular nozzle, and elliptical nozzle has the larger spray cone angel. They concluded that the combination of high injection pressure and elliptical orifice can increase the mass of entranced air, which can improve the spray and mixing quality.

Wager at el. [23] investigated the mixing and combustion of natural gas jets from circular and elliptical nozzle holes in an optically accessible combustion bomb. They found that peak heat release rates of the circular nozzle were higher, while the elliptical nozzle produced smoother transitions from premixed to diffusion burning. And they draw a conclusion that elliptical orifice can potentially reduce NOx and particulate emissions

Scholars have made some achievements in the study of the internal flow and spray behaviors with the application of non-circular nozzle, which has effectively promoted the progress of basic theories related to the non-circular nozzle spray, and these results also proved that non-circular nozzle has potential ability to improve the fuel and air mixture quality. However, the present researches about the non-circular orifices only focus on internal flow and spray characteristics, and these researches left out of consideration about the impacts of the actual working conditions, such as the constraints of combustion chamber boundary, airflow movement in cylinder, and variation of pressure and temperature. The effect of non-circular orifice on combustion process and emission performance of diesel engine in practical application needs to be research, and the related studies are rarely reported.

Therefore, in this paper, the circular and elliptical nozzles were drilled by the Laser Micro-Drilling (LMD) machining method. The influence of elliptical nozzles on combustion process and emission performance of diesel engines is studied, and the potential of elliptical nozzles on improving fuel economy and emission performance of diesel engines was verified.

2. Experimental Setup and Test Procedure

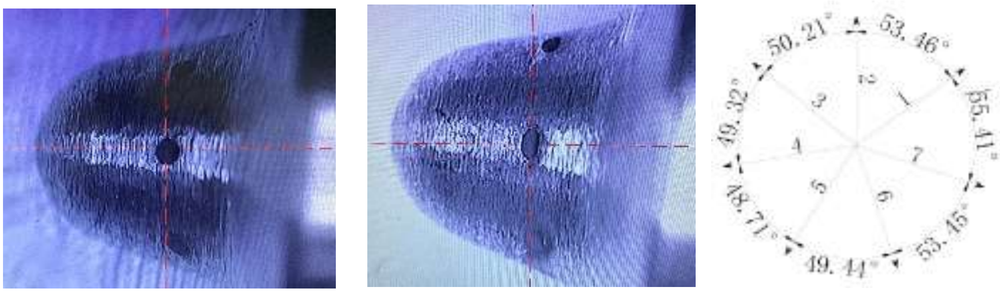
2.1 Experimental Setup

The engine specifications are provided in Tables 1. The test engine used in the present study was a four-cylinder, two-valve non-road diesel engine, and it was equipped with common-rail fuel injection system.

Tab. 1. The Engine and auxiliary equipment Specifications

Properties	Parameters
Engine Type	Two-valve, Turbocharged intercooled
Number of cylinders	4
Combustion Chamber	Re-entrant bowl
Bore(mm)×Stroke(mm)	95×115
Compression Ratio	17.5:1
Rated power(kW)/Speed(rpm)	75/2200
Peak torque (N.m)/Speed(rpm)	230/1600
Number of injection holes	7
Maximum injection pressure (MPa)	160

The present experimental study was performed with two different geometry nozzles: a non-conventional elliptical orifice and one with a standard circular orifice. The orifices were drilled by the Laser Micro-Drilling (LMD) machining method[24], which can ensure the precision of machining satisfactorily (±0.01mm). Each nozzle has seven orifices, topologies of two tested nozzles and the circumferential spatial distribution of the spray were provided in Fig. 1.



（a）circular （b）Elliptical

Fig. 1 The geometry and circumferential spatial distribution

The Nozzle specifications are provided in Tables 2. To isolate the influence of the orifice geometry, the cross-sectional areas are chosen to be the same in all cases and equivalent to the area of a circular section of diameter equal to 0.14mm. Other geometric parameters, such as orifice length, wetted perimeter and hydraulic diameter are also relevant for comparison. The hydraulic diameter was calculated by 4A/P, where A is the nozzle exit area and P is the wetted perimeter of the orifice.

Tab.2 Nozzle specifications

Nozzle	Major axis (μm)	Minor axis (μm)	Nozzle exit area (μm2)	Hydraulic Diameter (μm)	Orifice number
Circle	140	140	15393	140.0	7
Elliptical	171	114	15393	130.4	7

2.2 Test Procedure

The engine is controlled by the AVL Puma5 system. The Engine operating conditions and test equipment specifications are provided in Tables 3. The engine test was performed at 1600r/min^{-1} under three different loads (25%-78Nm，50%-156Nm， 75%-235Nm) . The reference nozzle (circular) was run first to set the speed and torque, when adjusting the engine with the nozzles having the elliptical orifices, the injection timing was set first, and then the fuel flow was adjusted until the same speed and torque as the reference nozzle was achieved. ETAS INCA 6.2 online calibration software was used to adjust fuel injection pressure and timing. The injection pressure was 80, 88 and 96MPa at three different loads ,respectively, and the injection timing was adjusted between -8 to -17° CA.

Tab.3 Engine operating conditions and test equipment specifications

Properties	Parameters
Speed (r/min^{-1})	1600
Load (%)	25，50，75
Intake air temperature (° C)	18±1
Cooling Water temperature(°C)	80±1
Injection pressure (MPa)	80, 88, 96
Injection timing (°CA)	-8 ~ -17
Dynamic control system	AVL Puma 5
Emissions	Horiba MEXA-7200D，AVL 415S
Dynamic fuel meter	AVL 733S
Combustion chamber pressure	Kistler 6052C
Combustion analyzer	AVL Indicom

The gaseous emissions and fuel consumption were measured by a Horiba MEXA-

7200D gas analyzer and AVL 733S fuel consumption meter, respectively. When engine condition and measurement instrumentation were stabilized, a one-minute average was taken for the engine readings in the Puma system. Exhaust smoke levels were sampled with an AVL 415S smoke meter, that provides results directly in FSN (Filter Smoke Number) averaged from three consecutive measurements under the same operating conditions. The obtained FSN value was converted into g/kWh by limits and measurement methods for emissions from light-duty vehicles.

A Kistler 6052C 01 piezoelectric pressure transducer was used to measure cylinder pressure at 0.1 crank angle degree increments, and Cylinder pressure was averaged for 200 cycles. The rate of heat release and other transient signal related curves were calculated by AVL Indicom Combustion analyzer.

3. Results and Discussion

3.1 Combustion characteristics

The in-cylinder pressure and rate of heat release (RoHR) at three operating conditions were used to compare the combustion characteristics of circular and elliptical nozzle. As shown in the Fig. 2, two-stage in-cylinder pressure peaks were observed at all conditions, indicating that combustion began after TDC (Top Dead Center). Compared with circular nozzle, all the second in-cylinder pressure peaks for the elliptical nozzles were lower, and with the increase of operation load, the pressure peak for the elliptical nozzles decreased more obviously. Compared with circular nozzle, the start of heat release for the elliptical nozzle was earlier. The RoHR was lower for the elliptical nozzles for a given crank angle degree CAD until the late combustion phase. In the late combustion phase the curves cross and the RoHR at late combustion was higher for the elliptical nozzle as shown in Fig. 2. The RoHR curves for 25% load did not have the same consistent pattern as the RoHR curves from 50% and 75% load. Single heat release rate peak was observed at low load. The maximum RoHR of the elliptical nozzle reduced by 23.1%, and the corresponding crank angle delayed by 0.2° CA at 25% load condition. Premixed combustion dominated the combustion process at 25% load condition that was different from 50% and 25% load condition. Two-stage heat release pattern was obtained at high load condition. The first stage was associated with premixed combustion as the second was associated with diffusion combustion. The maximum RoHR of the elliptical nozzle reduced by 22.4% and 16.5%, and the corresponding crank angle also delayed at 25% and 50% load condition. With the increase of the load, the amount of fuel injection increases, diffusion combustion dominates, and the maximum RoHR in the second stage is higher than that in the first stage. The maximum RoHR in the second stage for the elliptical nozzle reduced by 16.0% and 23.8%.

The prime reason for the above changes was that the ignition delay changes when used elliptical nozzle. In the present study, the ignition delay was defined as the interval that is from the start of the injection to the start of the combustion (SOC) which is the 5% point of the total value of accumulated heat release. As load increases, ignition delay decreased, and the ignition delays were shorter for the elliptical nozzles compared with the circular nozzle as shown in Fig.2 (d). With the decrease of operation load, the ignition delays for the elliptical nozzles decreased more obviously. The ignition delays shorten 0.5, 0.4and 0.3° Ca at 25%, 50%and 75% loads, respectively.

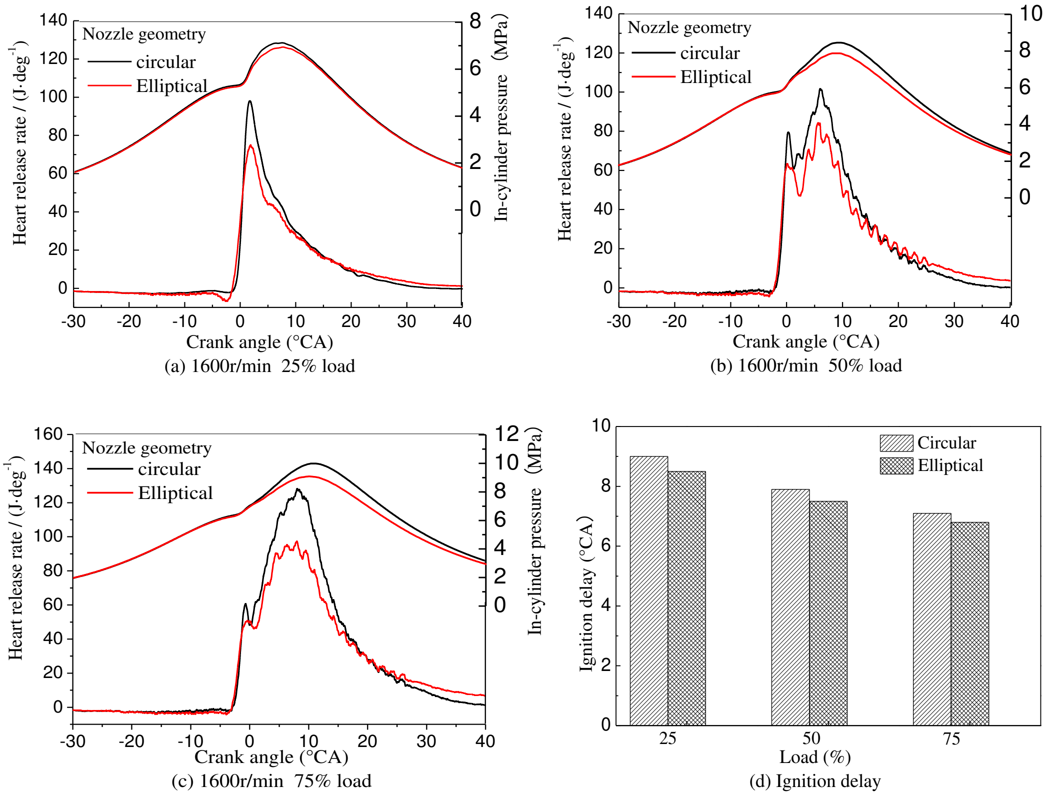


Fig. 2 The effect of nozzle geometry on in-cylinder pressure, RoHR and ignition

The average pressure and temperature at injection timing and Ignition timing were given in Tab. 4. The injection timing was -10° CA at all operation conditions, therefore average pressure and temperature in cylinder corresponded basically. However, the mixture of elliptical nozzle ignited earlier at lower temperature and pressure. Because the elliptical jet breakup faster and the elliptical jet breakup length was shorter, contact area of fuel and air was larger, which was helpful to increase the mixing intensity [13]. The mixing time for elliptical nozzle was shortened due to the early ignition. Lower heat release rate for the elliptical nozzles indicated that the reduction of mixing time plays a decisive role in the fuel-air mixing process under current nozzle and injection strategy. Although the mixing intensity for the elliptical nozzles was improved, the shorter mixing time results in less premixed-combustion, and shorter ignition delay proved to be the prime reason for lower heat release.

Tab. 4 Average pressure and temperature at injection and ignition time

Operating conditions	Nozzle	Average pressure (MPa) and temperature (K) at injection timing		Ignition timing (°CA))	Average pressure (MPa) and temperature (K) at ignition timing	
25% load	Circular	4.30	878	-1.0	5.30	913
	Elliptical	4.30	875	-1.5	5.23	894
50% load	Circular	4.70	885	-2.1	5.77	920
	Elliptical	4.70	884	-2.5	5.70	905
75% load	Circular	5.20	887	-2.9	6.35	923
	Elliptical	5.20	885	-3.2	6.27	913

The average temperature in cylinder was particularly critical to the emission performance of a diesel engine. The average temperature in cylinder for elliptical and circular nozzle at three operating conditions were given in Fig. 3. Typical curves of average temperature were observed under all the operate conditions. Compared with circular nozzle, the average temperature of the elliptical nozzle was lower obviously. The reduction of ignition delay and the RoHR for the elliptical nozzle were the prime reason for the reduction of average temperature. Thus, elliptical nozzle was beneficial to reduce NOx emissions. The combustion duration was shown in Fig. 3 (d), which defined as the interval from the start of the combustion to the end of the combustion which is the 95% point of the total value of accumulated heat release. The combustion duration of the elliptical nozzle was longer at different operation condition, with the increase of operation load, the combustion duration for the elliptical nozzle prolonged more obviously.

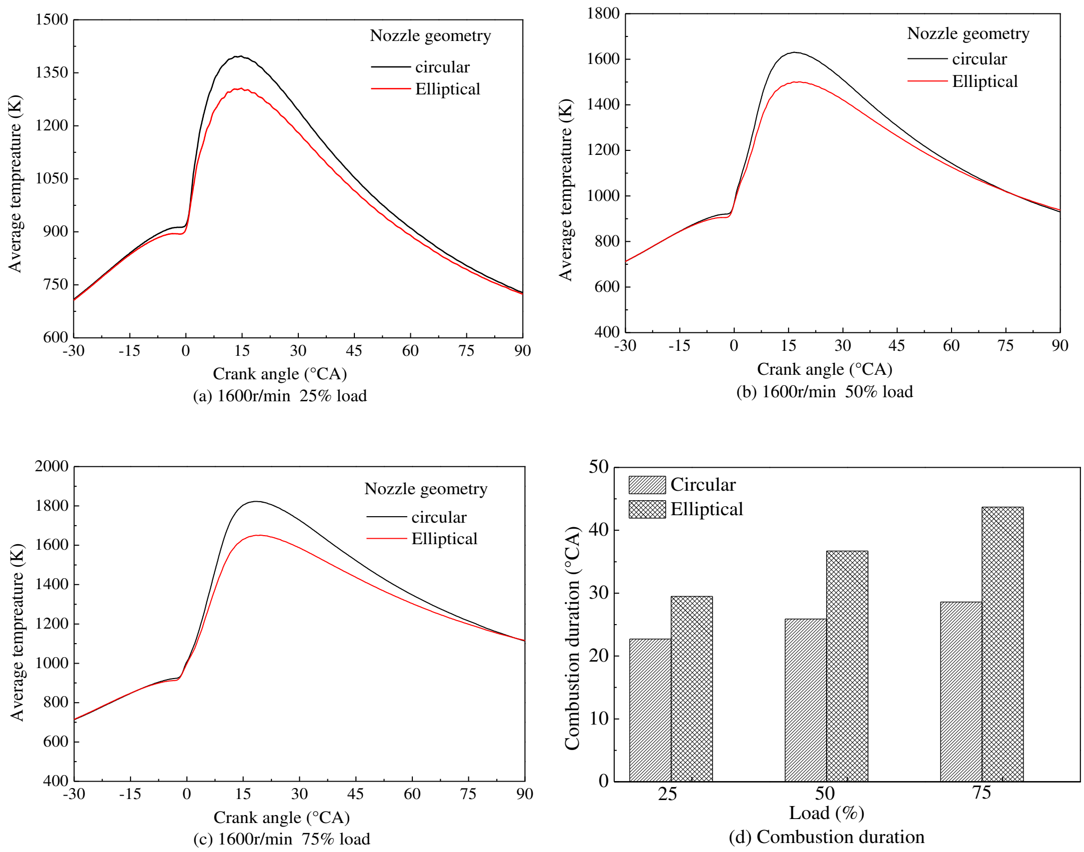


Fig. 3 The effect of nozzle geometry on average temperature and combustion duration

3.2 Exhaust emissions and fuel consumption

In the present study, the injection timing of reference circular nozzle at 25%, 50% and 75% load was -8, -10 and -11° CA, respectively. The effect of nozzle geometry and injection timing on Exhaust emissions and fuel consumption was were investigated at three operation conditions. The injection timing was varied from -8° CA to -17 °

CA, and all other control parameters were kept consistent.

The effect of nozzle geometry on NO_x and Soot emissions at different injection timing was shown in Fig. 4. It was observed that the NOx increased monotonically as the injection was advanced for elliptical and circular nozzle at all the operation conditions. The NOx emission for elliptical was significantly reduced, that resulted from the reduce in RoHR and average temperature in cylinder. Here a difference of 1.04~1.62 g/kWh was measured over the whole injection timing interval at 25% load, and 1.30~1.54 g/kWh at 50% load, and 1.03~1.27 at 75% load. Meanwhile, Soot emissions showed an opposite trend, it decreased monotonically as the injection was advanced. And shorter ignition delay and longer combustion duration for elliptical nozzle led to lower Soot emissions compared with circular nozzle. Here a difference of 0.006~0.016 g/kWh was measured over the whole injection timing interval at 25% load, and 0.019~0.092 g/kWh at 50% load, and 0.020~0.045 at 75% load.

The NOx-Soot trade-off was similar for all nozzles at the three loads as shown in Fig.4. However, the changers of exhaust emissions for elliptical nozzle offered the possibility of simultaneously reducing NOx and Soot emissions though adjusting the injection timing. Compared with reference point for circular nozzle, employing moderate earlier injection could improve NOx-Soot tradeoff of circular nozzle.

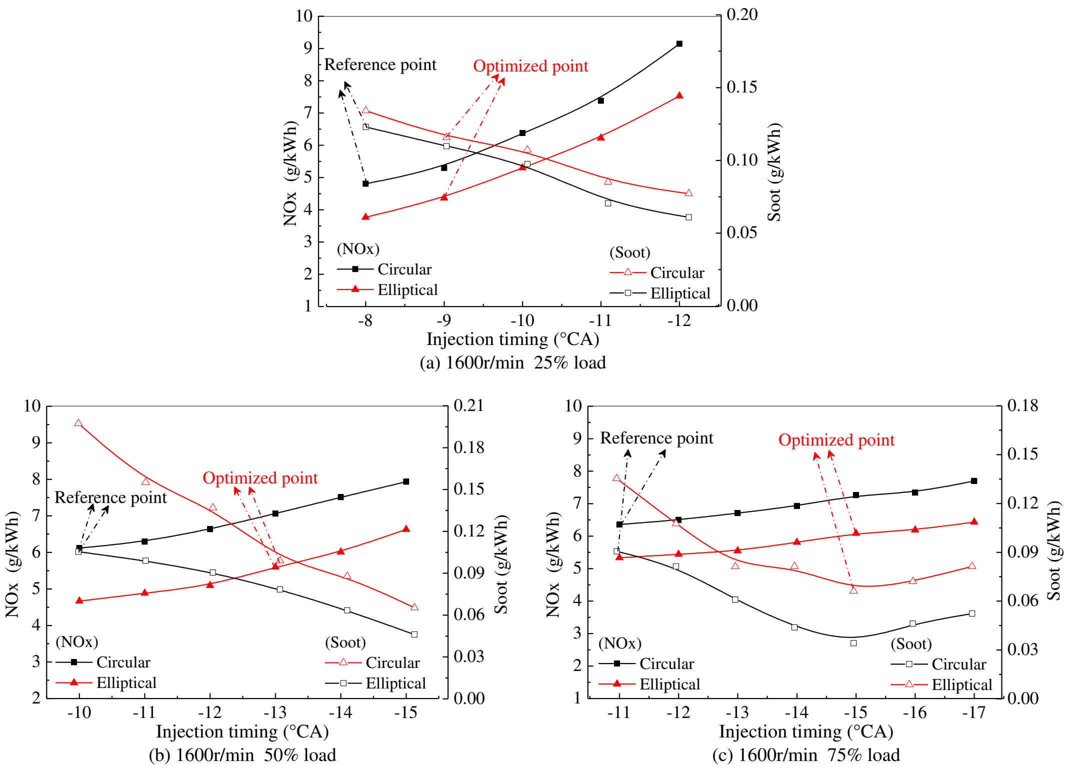


Fig 4 NOx and Soot vs. fuel injection timing

As shown in Fig.5, the NOx-fuel consumption trade-off was similar for all nozzles, and showed large improvements for the elliptical nozzles. Both fuel consumption for elliptical nozzles were lower over the whole timing interval, especially at low load condition, and fuel consumption for elliptical nozzles reduced slightly at the high load condition. There are two explanations could be the prime reason for the reduction of fuel consumption. The first is the lower rate of heat release for elliptical nozzle that is compensated with a lower heat flux loss. The second is the early ignition that led to combustion process closer to TDC. The larger the expansion ratio and the higher the thermal efficiency according to theory of thermodynamic cycle of diesel engine.

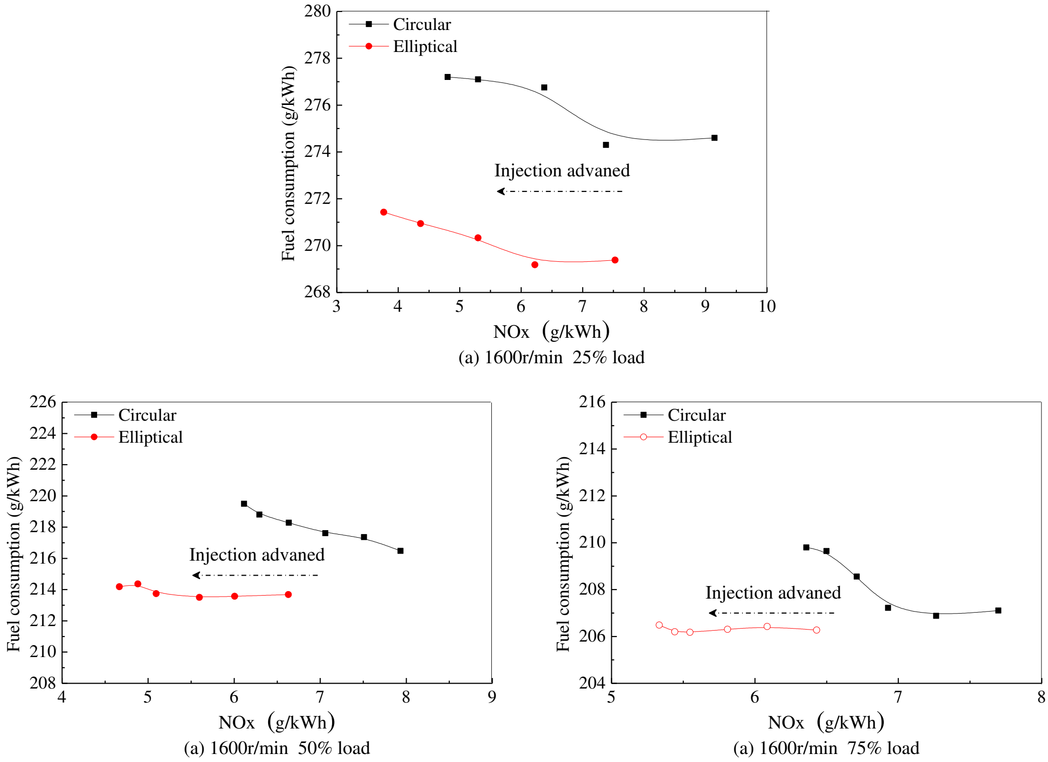


Fig 5 NOx and Fuel consumption vs. fuel injection timing

Compared with reference point for circular nozzle, employing moderate earlier injection could simultaneously improve performance of fuel economy and emissions. As shown in Tab.5, for elliptical nozzle and earlier injection, NOx emission reduced by 9.4%, 8.3% and 8.6%, and Soot emission reduced by 6.0%, 6.2% and 10.2%, and Fuel consumption reduced by 2.3%, 2.4% and 1.7% at 25%, 50% and 75% load respectively.

Tab. 5 Comparison results between reference circular nozzle and optimized point

load	Nozzle	Injection timing (°CA)	Nox (g/kWh)	Soot (g/kWh)	Fuel consumption (g/kWh)
25%	Circular	-8	4.81	0.123	277.2
	Elliptical	-9	4.36	0.116	270.9
50%	Circular	-10	6.11	0.105	218.8

	Elliptical	-13	5.60	0.099	213.5
75%	Circular	-11	6.36	0.091	209.8
	Elliptical	-15	5.81	0.081	206.3

4. Conclusion

The influence of nozzle orifice shapes on combustion process, exhaust emissions characteristics and fuel consumption were studied at three loads under varied fuel injection timing. The conclusions are given as follows:

(1) The ignition delays of elliptical nozzle are shorter result in the higher mixing intensity, but the reduction of mixing time plays a decisive role in the fuel-air mixing process. Therefore, the elliptical nozzles are characterized by longer combustion durations, lower maximum rates of heat release and in-cylinder average temperature.

(2) The NOx emission of elliptical nozzle is lower and Soot emission is higher. With using variable fuel injection timing, the NOx-Soot trade-off are affected by the nozzle shape. A substantial improvement in the Trade-off between fuel consumption and NOx emission is obtained for elliptic nozzles at three different loads.

(3) The result of the present experiment verifies the possibility of achieving improvement in NOx-Soot trade-off without penalty in fuel consumption based on employing moderate earlier injection coupled with elliptical nozzle.

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5. References

[1] Du W, Zhang Q, Zhang Z, Lou J, Bao W. Effects of injection pressure on ignition and combustion characteristics of impinging diesel spray. Appl Energ 2018;226:1163-8.

[2] Cung K, Bitsis DC, Briggs T, Kalaskar V, Abidin Z, Shah B, et al. Effect of Micro-Hole Nozzle on Diesel Spray and Combustion. SAE International.

[3] Xu Q, Xu M, Hung D, Wu S, Dong X, Ochiai H, et al. Diesel spray characterization at Ultra-High injection pressure of DENSO 250 MPa common rail fuel injection system. SAE International. 2017.

[4] Aravindh Kumar SM, Rathakrishnan E. Nozzle Aspect Ratio Effect on Supersonic Elliptic Jet Mixing. Journal of Fluids Engineering 2017;139(10). https://10.1115/1.4036823.

[5] Rathakrishnan E. AR 4 elliptic jet control with limiting tab. Fluid Dyn Res 2018;50(2):25505.

[6] Sekar M, Vijayaraja K. Acoustic and mixing characteristic of CD nozzle with inverted triangular tabs. International Journal of Ambient Energy 2017;39:1-19.

[7] Mohanta PK, Sridhar BTN. Study of decay characteristics of hexagonal and square supersonic jet. Int J Turbo Jet Eng 2017;34(2):115-22.

[8] Molina S, Salvador FJ, Carreres M, Jaramillo D. A computational investigation on the influence of the use of elliptical orifices on the inner nozzle flow and cavitation development in diesel injector nozzles. Energ Convers Manage 2014;79:114-27.

[9] Yu S, Yin B, Deng W, Jia H, Ye Z, Xu B, et al. Internal flow and spray characteristics for elliptical orifice with large aspect ratio under typical diesel engine operation conditions. Fuel 2018;228:62-73.

[10] Wang F, Fang T. Liquid jet breakup for non-circular orifices under low pressures. Int J Multiphas Flow 2015;72:248-62.

[11] Amini G, Dolatabadi A. Axis-switching and breakup of low-speed elliptic liquid jets. Int J Multiphas Flow 2012;42:96-103.

[12] Rajesh KR, Sakthikumar R, Sivakumar D. Interfacial oscillation of liquid jets discharging from non-circular orifices. Int J Multiphas Flow 2016;87:1-8.

[13] Farvardin E, Dolatabadi A. Numerical simulation of the breakup of elliptical liquid jet in still air. Journal of Fluids Engineering 2013;135(7).

[14] Yu S, Yin B, Deng W, Jia H, Ye Z, Xu B, et al. Numerical investigation on effects of elliptical diesel nozzle on primary spray characteristics by large eddy simulation (les). Atomization Spray 2018;28(8).

[15] Kasyap TV, Sivakumar D, Raghunandan BN. Flow and breakup characteristics of elliptical liquid jets. Int J Multiphas Flow 2009;35(1):8-19.

[16] Morad MR, Khosrobeygi H. Penetration of elliptical liquid jets in low-speed crossflow.

Journal of Fluids Engineering 2019;141(1).

[17] Ku K W, Hong J G, Lee C W. Effect of internal flow structure in circular and elliptical nozzles on spray characteristics[J]. Atomization and Sprays, 2011,21(8):655-672.

[18] Hong JG, Ku KW, Kim SR, Lee C. Effect of cavitation in circular nozzle and elliptical nozzles on the spray characteristic. Atomization Spray 2010;20(10).

[19] Kim SR, Ku KW, Hong JG, Lee CW. An experimental investigation of discharge coefficient and cavitation length in the elliptical nozzles. ILASS-Europe 2010, 23rd Annual Conference on Liquid Atomization and Spray Systems. Brno, Czechoslovakia. 2010.

[20] Sharma P, Fang T. Spray and atomization of a common rail fuel injector with non-circular orifices. Fuel 2015;153:416-30.

[21] Yu S, Yin B, Deng W, Jia H, Ye Z, Xu B, Xu H. Experimental study on the spray characteristics discharging from elliptical diesel nozzle at typical diesel engine conditions[J]. Fuel, 2018,221.

[22] Yu S, Yin B, Deng W, Jia H, Ye Z, Xu B, Xu H. An Experimental comparison of the elliptical and circular nozzles spray and mixing characteristics under different injection pressure[J]. Fuel, 2019,236.

[23] D wager. The influence of elliptical nozzle holes on mixing and combustion in direct injection natural gas engines, University of Toronto Toronto, ON, Canada,2008.

[24] Hasan M, Zhao J, Jiang Z. A review of modern advancements in micro drilling techniques. J Manuf Process 2017;29:343-75.