Available online www.jsaer.com

Journal of Scientific and Engineering Research, 2021, 8(10):60-66

Research Article

ISSN: 2394-2630
CODEN(USA): JSERBR

Effects of Equivalence Ratio on Combustion Characteristics of Port Fuel Injection Gasoline Engine

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Abstract The effect of equivalence ratio on the combustion characteristics of PFI engine was investigated by numerical simulation method, and a simulation model of four-stroke PFI engine was built by CFD software AVL-FIRE, and the effect of different equivalent ratio on the combustion performance of PFI engine was studied. The results show that in the range of 0.8-1.2 equivalent ratio, the instantaneous heat release rate, the highest combustion pressure in the cylinder and the temperature in the cylinder all increase first and then decrease with the increase of equivalent ratio. In this range, the combustion pressure and heat release rate of 1.1 equivalent ratios are the highest. Through comprehensive comparison, it can be concluded that under the simulated conditions, when the equivalence ratio is 1.1, the in-cylinder mixture formation quality is good, the combustion heat release rate is high, and the engine can obtain better combustion performance.

Keywords numerical simulation, equivalence ratio, combustion, heat release rate

Introduction

The concentration of the combustible mixture in the cylinder has an important influence on whether a stable flame core can be formed and its formation speed after spark plug is fired, and it is also one of the most important factors affecting flame propagation and combustion chemical reaction rate [1]. When the mixture is too thick, due to insufficient oxygen forced combustion is not sufficient, less heat release; When the mixture is too thin, too little fuel also leads to insufficient heat release. In both cases, stable flame core cannot be formed [2]. A large number of scholars at home and abroad has done experimental research on the influence of equivalent ratio on combustion characteristics. Sun [3] is based on a modified direct injection in cylinder of diesel engine spark ignition methanol engine, to study the different combustion space than mixture concentration distribution in cylinder, the combustion characteristic, the influence of the final results show that when the combustion space volume ratio increases, the maximum combustion temperature, maximum combustion pressure in cylinder and the peak heat release rate were significantly increased. Based on a diesel engine modified with in-cylinder direct injection methanol engine, Wang [4] studied the distribution of in-cylinder mixture concentration at different fuel ratio and determined that the specially modified injection hole could improve the mixture concentration near the spark plug. Gao [5] used numerical simulation to study the performance of ORP engines under different hydrogen direct injection strategies, and the results showed that the shortest combustion duration was about 18 (°CA) when the equivalent ratio were 0.577 –0.865.Sadatakhavi [6] studied the influence of equivalent ratio on tank combustion through experiments and numerical simulation, and the results showed that the combustion chamber temperature increased with the increase of total equivalent ratio. With the increase of equivalent ratio, incomplete combustion components decreased and combustion efficiency improved.

To sum up, a large number of scholars have explored the effect of equivalent ratio on engine combustion characteristics through experiments and numerical simulation. However, most of the selected equivalent ratio ranges are relatively limited. In this range, combustion characteristics tend to increase with the increase of equivalent ratio, and few studies are conducted on subsequent inflection points. In this paper, different equivalent ratios from thin mixture to thick mixture are successively selected, and the variation rules of engine combustion performance under different equivalent ratios under full load at full speed are systematically studied by numerical simulation, in order to find the appropriate equivalent ratio and make the engine achieve better combustion performance.

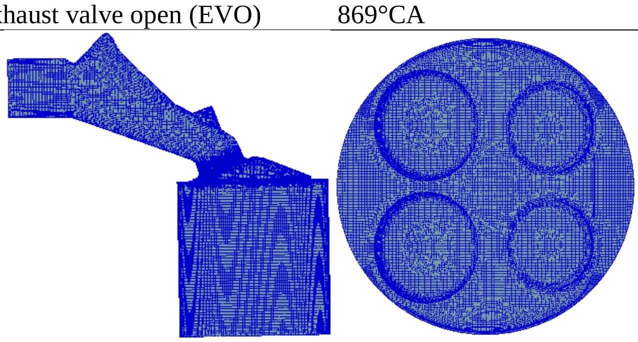
Establishment of numerical model

Computational grid

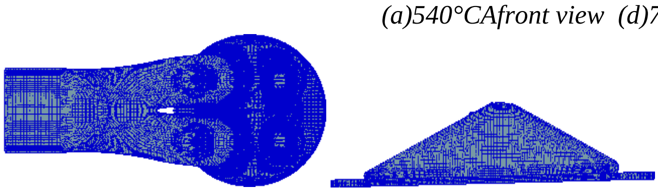
The basic engine parameters studied in this paper are shown in Table1.The computational domain of the established CFD model consists of the inlet, combustion chamber and piston. The computational grid is mainly hexahedral, and the near-wall area is fitted with unstructured grid. Dynamic grids of 360°CA (inlet valve opening Angle) to 581°CA (inlet valve closing Angle) and 581°CA (inlet valve closing Angle) to 869°CA (exhaust valve opening Angle) are generated by the FEP module in AVL-FIRE, with a maximum mesh size of 2mm. In the process of moving, large deformation will occur when the intake valve is opened or closed, so partial refinement of the intake valve and part of the valve seat is required, and the minimum mesh size is 0.3mm.The front view and top view of the moving grid at 540°CA and 720°CA are shown in Figure 1. The number of grids at 540°CA and 720°CA is about 950,000 and 380,000, respectively.

Table 1: Basic engine parameters

Name	Parameter
Engine type	Four-stroke, 4 valves
The cylinder diameter	80 mm
Connecting rod length	137 mm
Compression TDC	720°CA
Intake valve open (IVO)	360°CA
Intake valve closure (IVC)	581°CA
Exhaust valve open (EVO)	869°CA



(a)540°CAfront view (d)720°CAtop view



(b)540°CA top view (c)720°CAfront view

Figure 1: Moving grid view

Calculation model

The calculation model used in the simulation is shown in Table2, which adopts MPI parallel computing mode. The simple algorithm is used in the calculation process. In the case of strong turbulence and combustion, the simple algorithm can get better results. The flow control equation is discretized by the control volume method. For the dynamic meshes generated by FEP, Mirror (Mirror symmetry) with better adaptability is used for boundary value calculation, and least Sq. Fit (least square method) is used for derivative calculation. Least square method has better adaptability for meshes of different qualities and more accurate calculation, which is generally taken as the default option. The central difference scheme is used for continuity equation and momentum equation, and the upwind difference scheme is used for energy equation, turbulence governing equation and linear solution equation.

Table 2: Calculation model

Type	Model
Turbulence model	K-zeta-f
Wall heat transfer model	Standard Wall Function
Combustion model	ECFM
Spark ignition model	Spherical

The function of turbulence model is to try to describe the complex turbulent flow phenomenon, and the K-zeta-f four-equation model is selected in this paper. Its accuracy and stability are good, and the calculation time is only 15% longer than k-e model [7]. The ECFM extended correlation flame model is adopted in the combustion model, which describes the flame development process by calculating the flame surface density [8].

Boundary conditions and initial conditions

The calculated boundary conditions and initial conditions are shown in Table3. The engine speed is 5500r/min, and the study range of equivalent ratio is 0.8, 0.9, 1.0, 1.1, 1.2.Piston and intake valve are movable wall boundary, others are fixed wall boundary. Inlet mass flow is adopted as the boundary condition at the inlet, which is easier to converge calculation than pressure boundary [9]. The mass flow at the inlet is shown in Figure2, and temperature boundary conditions are used for other boundaries.

Table 3: Boundary conditions and initial conditions

Condition	Parameter name	Parameter setting
Boundary condition	Inlet temperature	330K
	Chamber top temperature	450K
	cylinder liner Temperature	450K
	Inlet valve temperature	330K
	Inlet valve seat temperature	330K
	Piston top temperature	450K
initial condition	Initial inlet temperature	325.5 K
	Initial inlet pressure	107369 Pa
	Initial turb.kin.energy of inlet	$0.001m^2/s^2$
	Initial temperature in cylinder	957.1 K
	Initial pressure in cylinder	115830 Pa
	Initial turb.kin.energy in	5 m2/s2

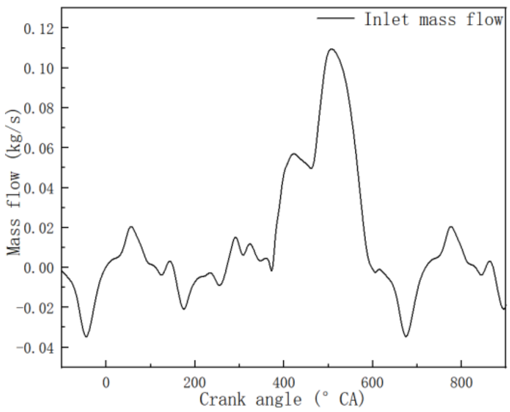
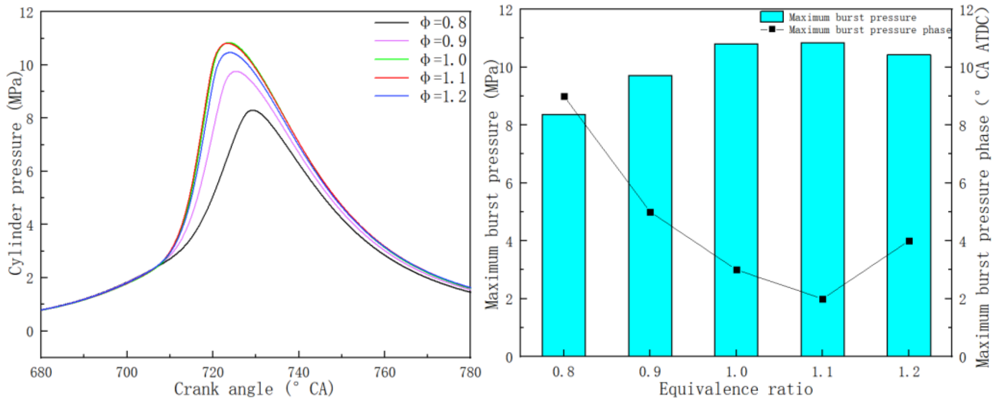


Figure 2: Inlet mass flow rate

Results & Discussion

Effect of equivalent ratio on combustion pressure in cylinder

Figure3 shows the changes of the average pressure, maximum burst pressure and phase in the cylinder under different equivalent ratios. The figure shows that with the increase of equivalent ratio, average pressure and the maximum explosion pressure in cylinder were first increases then decreases, while the maximum explosion pressure phase is, increase with the decrease of the first inflection point appeared in the equivalent ratio of 1.1, the maximum explosion pressure of the equivalent ratio of 1.1 10.84 MPa, the corresponding phase 2°CA ATDC, the mixture formation in cylinder quality is good. The burning tissue is more timely and the burning effect is good. When the equivalent ratio is 1.0, the maximum burst pressure is 10.81MPa and the corresponding phase is 3°CA ATDC. When the equivalent ratio decreases from 1.0 to 0.9, the maximum burst pressure decreases to 9.71MPa, the variation range is 10.18%, and the phase is delayed. When the equivalent ratio continue to decrease from 0.9 to 0.8, the maximum burst pressure drops to the minimum 8.36MPa with a variation of 13.9% and the phase is the last, which is mainly caused by too little fuel and too thin mixture. When it increases from 1.1 to 1.2, the maximum burst pressure drops to 10.43MPa with a variation range of 3.78%, and the peak phase is delayed, mainly because when the equivalent ratio increases to a certain extent, the mixture in the cylinder is too thick, which leads to slow flame propagation and combustion reaction rate, and the center of gravity of combustion moves backward.



(a) Cylinder pressure (b) Maximum burst pressure and its phase

Figure 3: Influence of different equivalent ratios on combustion pressure

Effect of equivalent ratio on local Mixture concentration and temperature distribution

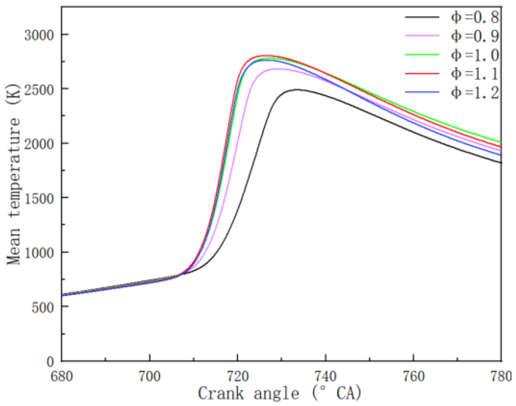
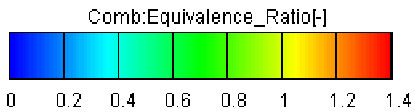


Figure 4: Mean temperature

The average temperature in the cylinder under different equivalent ratio conditions is shown in Figure 4. The peak value of the average temperature in the cylinder increases first and then decreases with the increase of equivalent ratio. The peak value of the temperature in the cylinder is 2806K when equivalent ratio 1.1. The equivalent ratio increases from 0.8 to 1.1, and the peak temperature rises from 2491K to 2806K. From 1.1 to 1.2, the peak temperature drops from 2806K to 2734K. The temperature with equivalent ratio of 1.1 has the fastest increasing rate and the earliest peak time, mainly because the mixture in the cylinder has good formation quality, high heat release rate and faster flame propagation and reaction rate, leading to higher increasing rate and peak value of the average temperature in the cylinder. The mixture concentration distribution in the cylinder at the ignition moment under different equivalent ratio is shown in Table4. The mixture concentration distribution in the combustion chamber is uneven at the ignition moment, and the high concentration of mixture is mainly distributed in the middle part of the combustion chamber near the spark plug. With the increase of equivalent ratio, the overall mixture in the combustion chamber gradually thickens. And the closer the area is to the spark plug, the more obvious the mixture concentration increases.Table5 shows the temperature distribution diagram of different equivalent ratio before and after TDC. At the same time, with the increase of equivalent ratio, the high temperature area near the spark plug and the temperature when the piston reaches TDC first increase and then decrease, and it reaches the maximum value at equivalent ratio 1.1.When the equivalent ratio is increased or decreased on the basis of 1.1, the high temperature region decreases, and the temperature at which the piston reaches TDC decreases. The overall high temperature region with equivalent ratio 0.8 is the smallest, and the temperature at which the piston reaches TDC is the lowest.

Table 4: Effect of different equivalent ratios on mixture concentration distribution at ignition time 697°CA



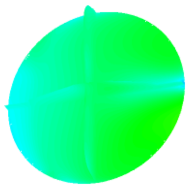
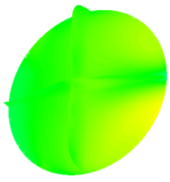
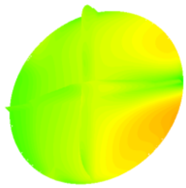
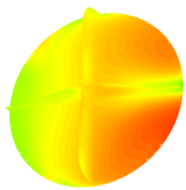
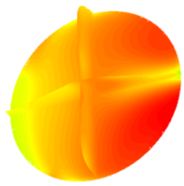
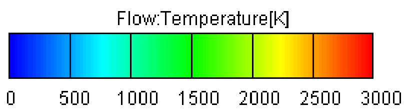
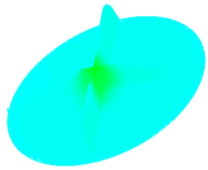
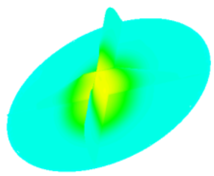
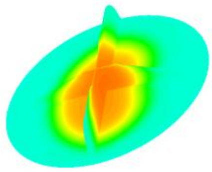
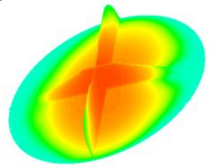
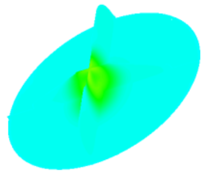
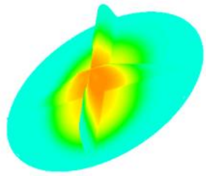
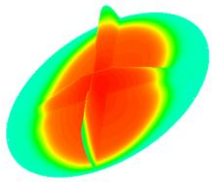
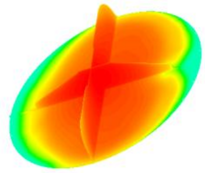
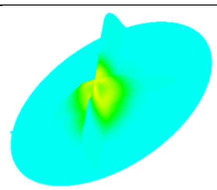
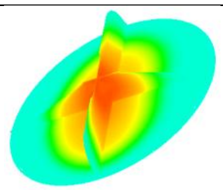
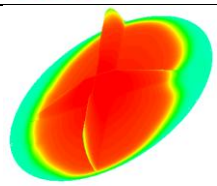
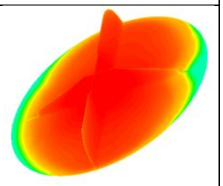
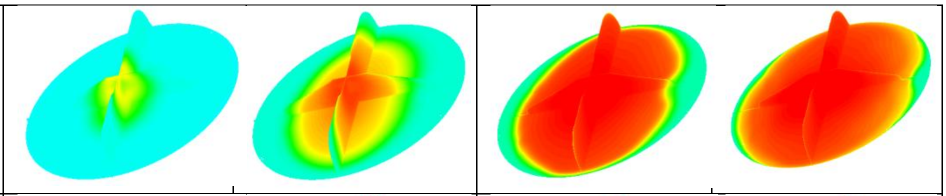
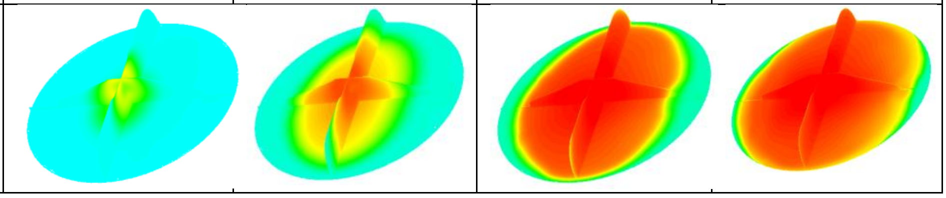
0.8	0.9	1.0	1.1	1.2
				

Table 5: Effect of different equivalent ratio on temperature distribution in cylinder



	10°CA BTDC	5°CA BTDC	TDC	5°CA ATDC
0.8				
0.9				
1.0				

1.1	
1.2	

Effect of equivalent ratio on heat release rate

Curves of heat release rate of different equivalent ratios are shown in Figure 5. As the equivalent ratio increases, the heat release rate increases first and then decreases. When the equivalent ratio is 1.1, the peak heat release rate is 122.36J/°CA, and when the equivalent ratio is 1, the peak heat release rate is 119.63J/°CA, which is slightly lower than that of 1.1. The reason is that when the mixture content in the cylinder is slightly higher, the concentration of free radicals required to maintain the combustion chemical reaction is larger, and the probability of chain break during reaction is smaller. Flame propagation and combustion reaction rates are faster, while the more fully reacted fuel, the greater the heat release, resulting in a higher peak heat release rate. Compared with equivalent ratio 1.1, the initial phase of combustion at equivalent ratio 1.2 is later, and the peak heat release rate is 113.78J/°CA, which is lower than that at equivalent ratio 1.1, mainly because when equivalent ratio increases to a certain extent, the mixture in the cylinder is too thick and uneven, which leads to slow flame propagation and combustion reaction rate, and the center of gravity of combustion moves backward. Thus, the peak value of the heat release rate drops, and when the equivalent ratio is 1.2, the slow decline of the heat release rate curve in the late combustion is due to the post-combustion of the over-concentrated mixture in the cylinder. The peak value of heat release rate with equivalent ratio of 0.8 is 68.58J/°CA.

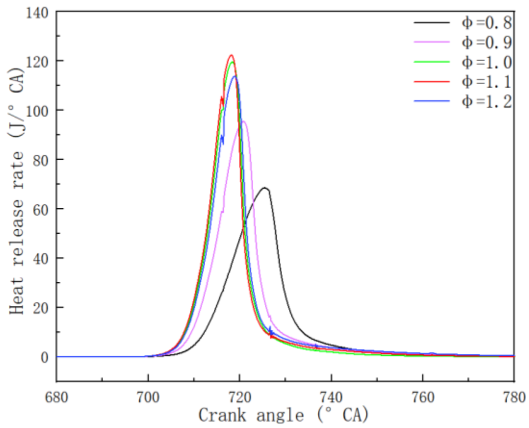


Figure 5: Heat release rate

Conclusion

In this paper, the influence of different equivalent ratios on combustion characteristics of PFI gasoline engine at full speed and full load was investigated by numerical simulation. The curves of in-cylinder pressure, temperature and heat release rate were compared under different equivalent ratios. The results showed that within the range of 0.8-1.2 equivalent ratios:

(1) With the increase of equivalent ratio, the average pressure in cylinder and the maximum burst pressure increase first and then decrease, the equivalent ratio increases from 0.8 to 1.1, and the maximum burst pressure increases from 8.36MPa to 10.84MPa. From 1.1 to 1.2, the maximum burst pressure decreases from 10.84MPa to10.43MPa, and the cylinder pressure reaches the maximum at equivalent ratio 1.1.

(2) The average temperature peak value in cylinder increases firstly and then decreases with the increase of equivalent ratio. When equivalent ratio 1.1, the maximum temperature peak value is 2806K, and the equivalent ratio increases from 0.8 to 1.1, and the temperature peak value rises from 2491K to 2806K. From 1.1 to 1.2, the peak temperature drops from 2806K to 2734K.
(3) With the increase of equivalent ratio, the heat release rate increases first and then decreases. The equivalent ratio increases from 0.8 to 1.1, and the peak heat release rate increases from 68.58J/°CA to 122.36J/°CA, and the peak phase advances. The equivalent ratio increases from 1.1 to 1.2, the peak heat release rate drops from 122.36J/°CA to 113.78J/°CA, and the peak phase is delayed.
To sum up, it can be concluded that under the simulated conditions, the engine can achieve better combustion performance and power performance when the equivalence ratio is 1.1.

Acknowledgment
The authors wish to thank Shandong Provincial Natural Science Foundation, China (ZR2017LEE019 and ZR2013EEQ005) for their support of this study.

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