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Computational and experimental study on TR combustion system of diesel

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Abstract：A new combustion system applied in the 135-type diesel engine — TR(Three-Rapidity)，was modified from deep cave ω combustion chamber with an oriented arc in the middle of chamber wall，and perfectly fit to a nozzle with orifices in conic section plus orifice in the center. Three-dimensional numerical simulation was completed and compared between TR combustion system and original 135 diesel engine combustion system in 50% load by STAR-CD. The results show that in TR combustion system，fuel ignition location is near TDC，and premix combustion proportion increases. The oriented arc，contracted cave and centric spray contribute to enhancing air flow，making more reasonable fuel distribution and forming more homogeneous mixture. The usage of air in chamber is effectively increased and heat loss from the chamber wall is obviously decreased. The cold start performance of the engine is also improved. A performance test on TR combustion system was made on a 135-type diesel engine. The results demonstrate that TR has better exhaust smoke than the original engine. At the low and moderate load，NO_x emission of TR combustion system is less than the original system，but more in high load condition，which can be solved by delaying fuel spray timing. TR combustion has much potential to improve emission with less structural change of the original engine.

Key words：diesel；combustion chamber；numerical simulation；spray

0 Introduction

The mixture formation is the key to control the combustion process of diesel engine. It includes two aspects：One is the fuel atomization and the other is the airflow organization. According to this concept，TR (Three-Rapidity) diesel combustion system was brought forward in Lit. [1]，which is characterized by rapid fuel-injection，rapid formation of mixture and rapid combustion. It was modified from deep cave ω combustion chamber with an oriented arc in the middle of chamber wall，and perfectly fit to a nozzle with orifices in conic section plus orifice in the center. Its performance was studied in a single cylinder diesel engine and was found to be effective [1,2].

In the recent years，the development of computational fluid dynamics (CFD) provides a lot of support to the design and manufacture of the engine. It has closely integrated the structure parameters and geometric shape with the visual demonstration of the flow field in

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combustion chamber. The informatively calculated results, which are in general hardly measured, provide clearly and accurately the understanding of mixture formation mechanism and combustion process. By means of CFD, the development of the new type engine and new combustion system was greatly shortened in time and easily guided to be success[3,4].

In the paper, three-dimensional numerical simulation of TR combustion system was completed by STAR-CD. The emphases of investigation are on the mixture formation and combustion process. The airflow, turbulent kinetic energy distribution, the mixture formation and combustion were analyzed and compared with the computed results of the original combustion system of 135-type diesel engine.

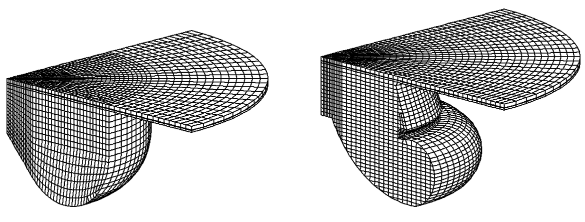
1 Computational scheme

The STAR-CD code is based on the Finite-Volume approach where the computational domain is divided into control volumes with a computational mesh. The PISO arithmetic is used in numerical procedure. In virtue of models describing airflow, spray, combustion and emission, STAR-CD is suitable to in-cylinder airflow and combustion with advantages in diesel engine. High Reynolds number k-ε turbulence models were determined in simulation. Huh model describes the fuel atomization, which assumes that the original turbulence of the jet current surface generated in the nozzle hole does not stop disturbing with exponential increase due to aerodynamic interaction, until droplets are detached from the jet current.

Reitz/Diwakar model was selected as droplet break-up model. The non-uniform pressure field around the droplet causes it to expand in the low pressure wake region and eventually disintegrate when surface tension forces are overcome. This case is called "Bag break-up". The other one is "Stripping break-up", in which liquid is sheared or stripped from the droplet surface. The break-up criteria is based on the droplet Weber number and the droplet Reynolds number.

Fuel impinging on the wall is affected by many factors, such as droplet velocity, incident angle, wall temperature and so on. The physical phenomena of impingement are stick, rebound and splash. Bai model distinguishes the different impingement regimes from the above by droplet Weber number and the Laplace number. The shell autoignition is applied as ignition model. The combustion model is eddy breakup model(EBU), brought forward by Magnussen, which can be used in both premixed and diffusion combustion[5,6].

Considering axisymmetric cylinder, a quarter of the chamber is constructed for computational mesh, saving the computational resources. Computation starts from intake valve closed timing (140 ℃A BTDC) to 140 ℃A ATDC. TR combustion system has deep cave ω combustion chamber with contractive throat. In contrast, the original chamber of 135-type diesel engine is ω combustion chamber with vertical wall. The computational grids on the TDC are shown as Fig. 1.



(a) ω combustion chamber (b) TR combustion chamber

Fig. 1 Computational grids of combustion chamber

The specifications of 135-type diesel engine are shown in Tab. 1. The nozzle with 4×ϕ0.36 mm orifices in conic section plus 1×ϕ0.20 mm orifice in the center is used in TR combustion system. The ω combustion system has the nozzle with 4 × ϕ0.36 mm orifices. The injection quantity is 95 mm^3 per cycle, which was measured when the engine was in 50% load. Based on the experimental results, the temperature is assumed to be 320 K, 520 K, 500 K and 500 K respectively corresponding to initial air, cylinder head, piston top and cylinder wall. And the initial pressure is 0.1 MPa. The boundary on the symmetrical side is cyclic boundary, and others are wall boundary. The moving piston is described by a subroutine which deals with the velocity of the piston.

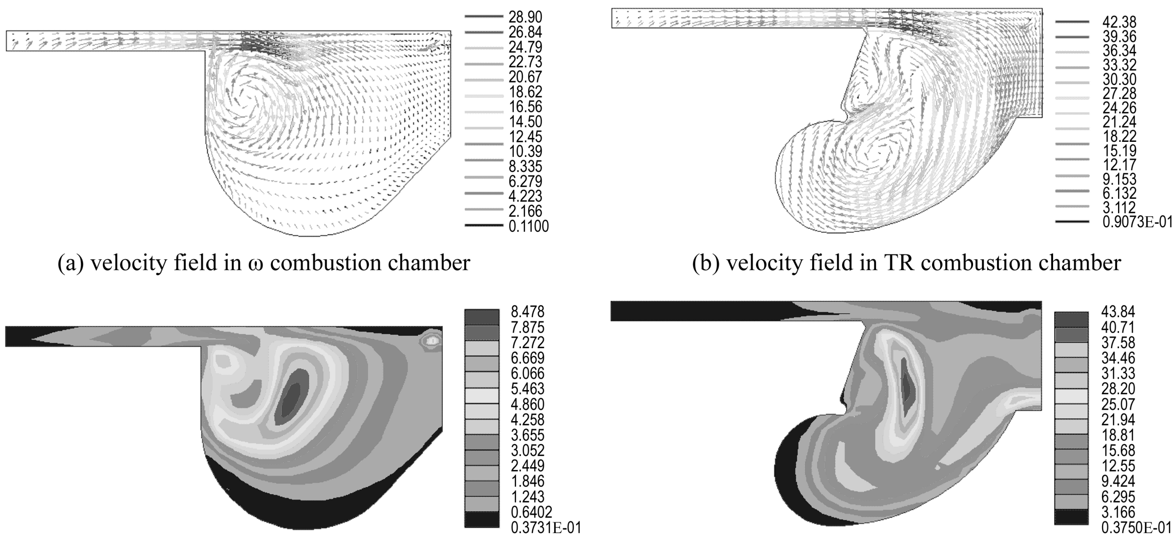
Tab. 1　Diesel engine specifications

parameters	value
bore/mm	135
stroke/mm	150
connecting rod/mm	265
speed/($r \cdot min^{-1}$)	1 500
spray angle/(°)	150
injection pressure/MPa	20
injection angle/°CA BTDC	11
air temperature/K	320
air pressure/MPa	0.1
compression ratio	16.8
power/kW	14.7

2　Results and discussion

2.1　Velocity field and turbulent kinetic energy in spray time

Fuel is injected into cylinder at the 11 ℃A BTDC. The comparison of velocity field and turbulent kinetic energy in the combustion chamber in the vertical plane and through nozzle orifice axes are shown in Fig. 2. In the late period of compression stroke, the majority of air in the cylinder is squashed into the chamber. This kind of air flow is called "squish". Strong squish can induce small scale turbulent of airflow, quickly mixing fuel vapour with air in molecular scale. Seeing from Fig. 2(a) and 2(b), squish area is smaller in ω combustion chamber than in TR combustion chamber, and the vertical wall has less advantage to forming squish than the contractive throat. Furthermore, in ω combustion chamber, there exists only a moderate intensity clockwise eddy at the throat, but in the other area which is weak, generally less than 3 m/s. In TR combustion system, the contractive throat and the convex lobe at the bottom center of the chamber lead the compressed air flowing along the cave wall in a large intensity clockwise eddy. When airflow meets with oriented arc lobe on the chamber wall, the moving direction is changed, forming a small anticlockwise eddy near the slope wall. The intense airflow (the highest speed is 42.38 m/s), large squish area



(a) velocity field in ω combustion chamber　(b) velocity field in TR combustion chamber

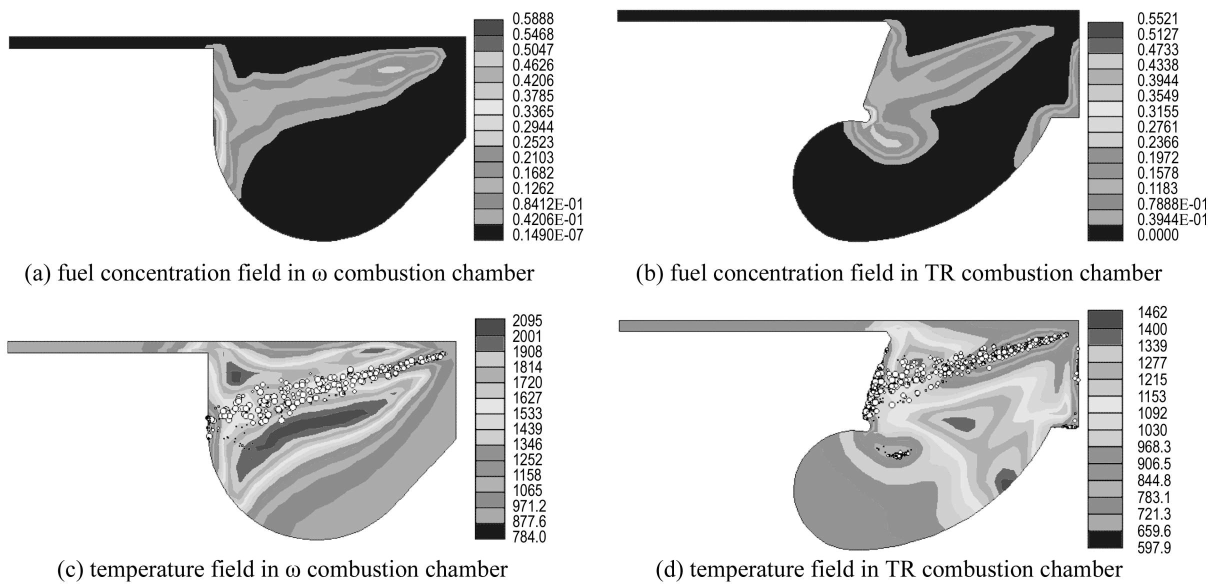
(c) turbulent kinetic energy in ω combustion chamber　(d) turbulent kinetic energy in TR combustion chamber

Fig. 2　Comparison of velocity field and turbulent kinetic energy in the combustion chamber and obvious anisotropic velocity are favorable to mixture formation in whole chamber. Especially, the strong eddy makes the fuel film formed by fuel spray impingent on the oriented arc lobe vaporize faster and reduce the fuel coating on the wall.

The distribution of turbulent kinetic energy is shown in Fig. 2 (c) and (d). In ω combustion chamber, the maximal turbulent kinetic energy is only 8.478 m^2/s^2 and concentrates on the up part of the chamber. But in the atomization area surrounding the fuel spray, the turbulent kinetic energy is too weak to highlight the mixture formation and combustion. By contrast, in TR combustion chamber, the turbulent kinetic energy in the chamber is much higher and the maximal turbulent kinetic energy reaches up to 43.84 m^2/s^2. The importance is that the high turbulent kinetic energy locates all over the chamber cave and oriented arc lobe area which is favorable to fuel atomization. Comparing combustion system of 135-type diesel engine, TR has the intense airflow and turbulent kinetic energy with the reasonable action region and distribution. Therefore, the fuel atomization and mixture formation are significantly improved.

2.2 Fuel concentration field and temperature field in ignition time

Fuel begins to fire at 1 °CA BTDC in TR combustion system and at 2.5 °CA BTDC in ω combustion system. The temperature and concentration distributions at firing point are shown in Fig. 3. The fuel concentration is expressed by fuel mass fraction of fuel vapour mass in the cell to total mass in the cell.



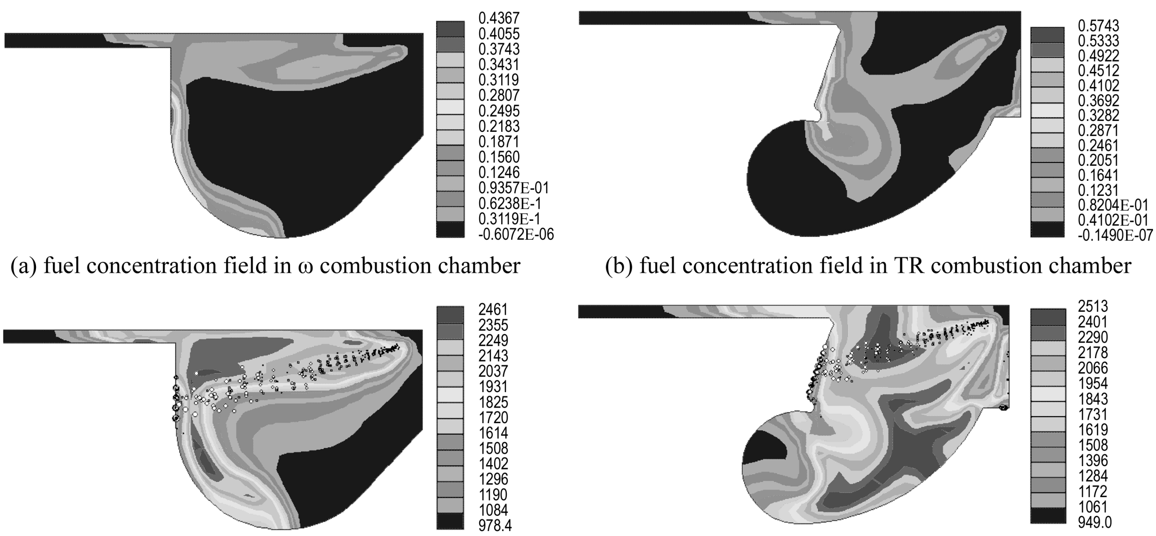
(a) fuel concentration field in ω combustion chamber
(b) fuel concentration field in TR combustion chamber
(c) temperature field in ω combustion chamber
(d) temperature field in TR combustion chamber

Fig. 3 Comparison of fuel concentration field and temperature field in the combustion chamber

Shown as Fig. 3 (a) and (b), in ω combustion system the spray jet sufficiently develops. The spatial vaporization is dominant. Wall jet formed after fuel impinges on the wall continuously moves along the side wall. In the TR combustion system, the distance between nozzle and wall becomes short, so that most fuel keeps liquid state when impinging happens. Much more fuel droplets stick on the wall. The oriented arc lobe changes direction of the wall jet and makes it turn back to the center of the chamber. The secondary fuel atomization occurs. Eventually, the air entrainment gains tremendous increase, and the amount of mixture is rapidly generated[7]. In TR system, the fuel injected from central orifice impinges on the plane convex at the bottom and moves flatly. It diffuses along cave bottom when it leaves the plane. Because of having small orifice and fine fuel droplet, the mixture is formed quickly near the center of chamber. On the other hand, since the temperature in the chamber center is higher, it is essential to autoignite the fuel/air mixture and to start the engine in the cold condition. The lean mixture formed at early stage is blown by the squish to offset downwards the spray, forming the second ignition point. The rich mixture over spray beam is exposed to the low temperature, herein forming the third ignition point. Depending on the discussion above, it is concluded that the central orifice spray improves the fuel distribution, the combustion sequence is under control and many points are ignited orderly. In ω combustion chamber, spray is gently affected by the squish, and firing point is concentrically around it. Fig. 3 (c) and (d) show the temperature in these two chambers. In the TR chamber, more dispersive combustible mixture offers a necessary condition for multi-points firing in relatively moderate temperature. The high temperature is illustrated in Fig. 3 (d) to be 1 462 K. Lots of fuel droplets distribute in the low temperature area and the phenomena of "fuel surrounding fire" are reduced. But in ω combustion chamber, the temperature reaches 2 095 K and high temperature area is larger, which increases the probability of NO_x formation.

2.3 Fuel concentration field and temperature field in main combustion period

The fuel injection is finished at 5 °CA ATDC. The fuel concentration and temperature distribution are shown in Fig. 4. In Fig. 4 (a), the wall-jet develops along the wall to cave, forming fuel film and rich mixture at bottom. If the air near this area is insufficient or the proper mixture is not available, the combustion will be incomplete. In addition, affected by cold wall, it becomes worse, which leads to emitting more soot and HC. Most unburned mixture exists in the clearance volume and the squish lip of chamber. Here flame quenching will happen for the low temperature and slow airflow. So it becomes another resource generating soot and HC. Fig. 4 (b) shows the mixture concentration distribution of TR system. The unburned mixture generally gathers round the bottom and lower part of the chamber. It is exposed to high temperature, and



(a) fuel concentration field in ω combustion chamber　(b) fuel concentration field in TR combustion chamber

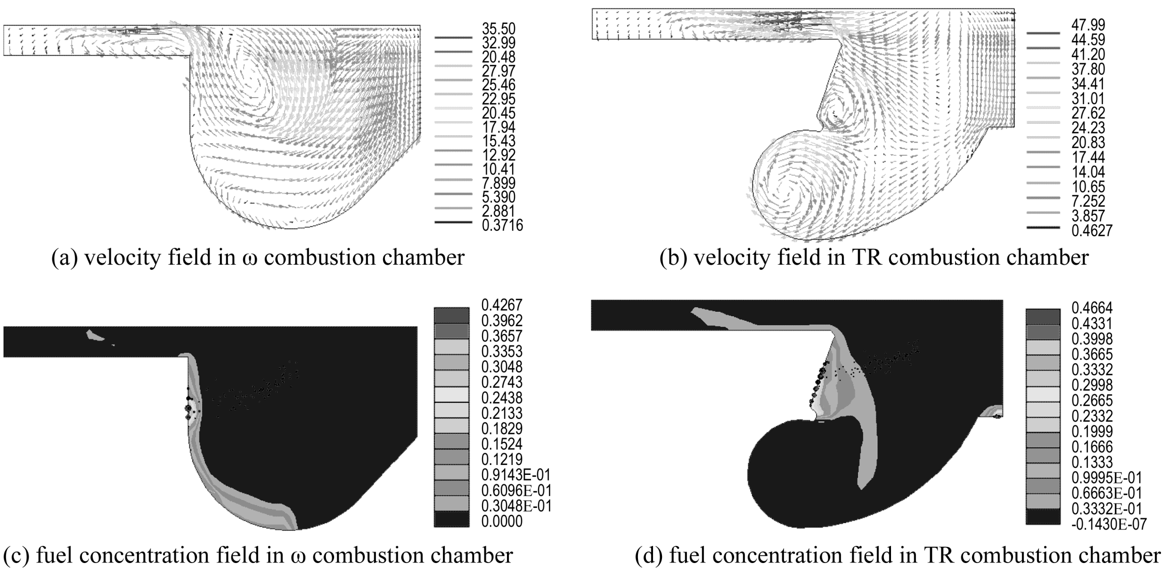
(c) temperature field in ω combustion chamber　(d) temperature field in TR combustion chamber

Fig. 4　Comparison of fuel concentration field and temperature field in main combustion period continuously vaporize and combust. The contractive throat of chamber prevents too much unburned mixture from going into clearance volume. As a result, soot and HC are diminished largely.

Fig. 4 (c) shows the temperature patterns in ω combustion chamber. Because there is scarcely fuel and weak airflow movement in the chamber center, the combustion hardly happens, so that the temperature is lower and air is not made full use of. The high temperature area is located in the periphery and lip of the chamber. In contrast, as shown in Fig. 4(d), TR chamber has the high temperature in the center and the low temperature near the wall. The fuel bounced back to the center by the oriented arc lobe as well as injected by the centric orifice results in the rich mixture in combustion space. The current leaner unburned mixture is held in the circumambience. The flame propagates from the center to the outside. The temperature adjacent to combustion space wall is relatively low. Generally, TR combustion system has a reasonable mixture formation and combustion process.

2.4 Velocity field and fuel concentration field in late combustion period

Fig. 5 shows the velocity and concentration field at 15 °CA ATDC. The majority of mixture has been combusted. At the moment, squish and combustion turbulence further promote the gas movement, accelerate mixture formation and improve diffusion combustion. Seen from Fig. 5 (b), the turbulence strength in TR system is still greatly strong. The cause is that the contractive throat of chamber guides the airflow direction. The strong turbulence enhances the flame propagation and the transfer of the burned and unburned components. The diffusive combustion duration gets shorter and the soot significantly minimizes, which makes preparation for depressing NO_x by delaying fuel injection timing.



(a) velocity field in ω combustion chamber (b) velocity field in TR combustion chamber

(c) fuel concentration field in ω combustion chamber (d) fuel concentration field in TR combustion chamber

Fig. 5 Comparison of velocity field and fuel concentration field in late combustion period

There is a middle scale eddy adjacent to combustion space wall up the oriented arc. The fuel film adhering to the wall vaporizes by the means of it, meanwhile, joins the combustion. In the cave there is a large scale clockwise eddy. This eddy brings the fresh air into the vapor stirred up from the fuel film and sequentially brings the burned gas into the center of chamber. It is favorable to the last period of combustion. In ω combustion chamber, there is only a medium-scale eddy near the lip. The air near wall and in cave moves too slowly to blow off the film. So the combustion is not completed like in TR system.

2.5 Comparison of experimental study

The emission of TR combustion system is measured in a single cylinder 135-type diesel engine whose speed is 1 500 r/min and compared with the original engine data. The smoke and NO_x concentration with different loads are shown in Fig. 6, 7. In Fig. 6, with the load increasing, the smoke increases too and the smoke of TR is lower than that of the original engine. In 25% load, the smoke is 0.27 BSU, 85% of the original one. In the rated load, the smoke is 0.6, decreases by 90%. In the Fig. 7, the NO_x concentration of TR system increases with the load increased because more fuel is injected into the cylinder, which leads to higher temperature. When the load is less than 90%, the NO_x emission of TR system is less than the original system. In 50% load, NO_x concentration of TR system is 307×10^{-6}, 55.2% of the original one, which is in agreement with the calculated result. But in the 90% and 100% of the rated load, it is higher. The increment is up to 30% at the rated load. When the load of the original engine is greater than 90%, the air in the combustion chamber is insufficient according to the fuel which makes combustion get worse. Less air reduces NO_x concentration even if the temperature in the cylinder is higher, so the NO_x concentration of original engine reduces. In TR combustion system, the mixture formation is better and air is used enough, which increases NO_x concentration more and more higher. So TR has more NO_x emission than the original engine in high load. Delaying the fuel injection timing can solve this problem with a little smoke increased[8], since the smoke emission of TR system is excellent. The performance test shows that TR combustion system has much potential in emissions and performance.

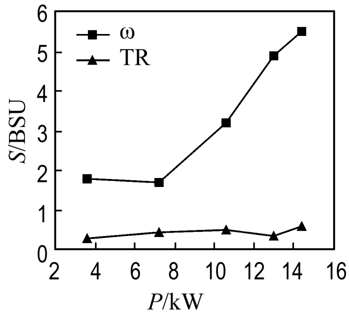


Fig. 6　Smoke changing according to the load (1 500 r/min)

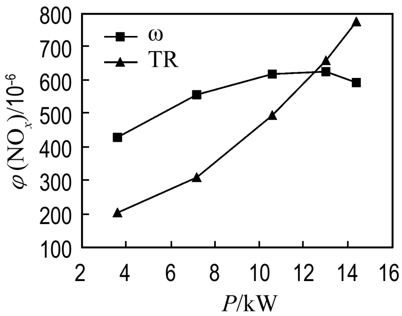


Fig. 7　NO_x changing according to the load (1 500 r/min)

3 Conclusions

(1) TR system forms strong squish in the compression stroke. Oriented arc lobe changes the distribution of velocity field and turbulent kinetic energy. The number of eddies and their distribution region increase greatly, which makes the fuel vaporize quickly.

(2) The mixture evenly distributes in combustion space. The highest temperature area is located in the center of chamber. The flame propagates from the center of the chamber to the outside. The fresh air is made full use of.

(3) The small centric orifice effectively improves fuel distribution and the fine droplet is beneficial to cold start.

(4) Experimental study shows that TR has

low smoke emission in all load conditions. NO_x is lower than that of the original engine except for the high load condition. TR combustion system has a promising application to diesel engine.

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柴油机 TR 燃烧系统模拟与试验研究

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摘要: 一种应用在135柴油机上的新型燃烧系统TR(Three-Rapidity),是由收口深坑ω形燃烧室改进而成,在壁面设置导向圆弧,并与带中孔的多孔喷嘴相匹配. 应用STAR-CD软件对TR燃烧系统在50%负荷下的工作过程进行三维数值模拟,并与原机燃烧系统相比较. 结果表明,TR燃烧系统的着火点控制在上止点附近,增加了预混合燃烧的比重. 采用导向圆弧、缩口燃烧室和中孔喷射,气流运动更加剧烈,燃油空间分布合理,空气利用充分,减少壁面散热损失,并具有良好的冷启动性能. 在135单缸柴油机上进行试验研究,和原机相比TR燃烧系统具有良好的烟度排放特性,NO_x 排放在中小负荷低于原机排放,在高负荷则有所增加,可通过推迟喷油来解决. TR燃烧系统在降低柴油机排放方面具有较大的潜力,对原机结构改动较少,具有广阔的应用前景.

关键词: 柴油机;燃烧室;数值模拟;喷雾

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