Int. J. Energ. Water Resour., 1(1): 19-26, Winter 2017

Rotating injector in DI diesel engine for improving performance and reducing NO_x emission

K. Sengottaiyan; M.R. Swaminathan

Internal Combustion Engineering Division, Anna University, Chennai-600 025, India

Received 7 June 2016; revised 14 October 2016 accepted 20 November 2016

ABSTRACT: Oxides of Nitrogen are the major emission from a diesel engine. It is due to heterogeneous diffusion combustion system with fuel-rich regions which produce high local temperature around the periphery of the spray where high formation rate of NO is promoted. Various techniques are therefore employed to reduce the NO_X emission like EGR, SCR, etc. In the present work a rotating injector is used as a technique for improving performance and reducing NO_X emission in a direct injection diesel engine. The conventional stationary injector is replaced by the rotating type of injector to spray the fuel inside the engine cylinder. This rotating injector is functionally modified to achieve the rotary motion of the injector during injection. The fuel injector is rotated during the fuel injection which creates a fuel swirl motion inside the cylinder. The emission and performance of a single cylinder diesel engine using modified rotating injector at various loads are studied. The investigation reveals reduced NOx emission and marginal improvement in the performance of the engine due to decrease in breakup length of spray and increase in the spray area during injection. The rotating spray makes co-swirl motion along with air swirl motion inside the cylinder at the end of the compression. The finer fuel is sprayed throughout the combustion chamber, enhancing the air fuel mixing process. It increases the burning rate and reduces the local concentration of the mixture. As a result, there is an improvement in performance and a simultaneous reduction in NO_X emission from the engine.

Keywords: *NO_X emission; Rotating injector; Swirl; Three hole nozzle*

INTRODUCTION

The diesel engine is a compression ignition engine, in which the fuel is ignited solely by the high temperature created by compression of the air-fuel mixture. This engine operates on the diesel cycle. The diesel engine is more efficient than the petrol engine, since it operates with a higher compression ratio and lower air fuel ratio. In the diesel engine, fuel injection systems plays an important role in reducing the emission To achieve this, various fuel injection system like indirect injection system, multi hole nozzle fuel injectors, common rail direct injection system (CRDI) etc. are being developed. The Above techniques are mainly concentrated on reducing the emission and improving the performance of the engine. NO_X emission is comparably higher than other emissions. Rotating Direct Injection (RDI) is a new technique that can be employed to decrease the NO_X emissions and to improve the performance of diesel engines (Cipolat 2007).

In diesel engine combustion process, when fuel injection pressure is low, fuel droplet diameters will increase, increasing the also ignition delay period during the combustion which increase the NO_X emission. If the injection pressure is too high, ignition delay period becomes shorter and there is a possibility of making very small droplets, which produce higher combustion temperature and increases NOx formation (Konstanzer *et al.,* 1998; Sjoberg 2000). RDI system in a direct injection diesel engine is aimed to achieve a

*Corresponding Author Email: senengg2@gmail.com
Tel.: +91 99 6205 3033 Fax: +91 99 6205 3033

high degree of atomization, in order to have sufficient spray evaporation in a very short time and to achieve sufficient spray penetration in order to utilize the full air charge. When the fuel injector rotates particle diameter size will become small. Since mixing of fuel with air becomes better during ignition period, engine performance will increase.

Rotating injectors differ from the conventional type of fuel injector in that the fuel passing through the orifice has a swirling motion, so that the resultant spray has a large cone angle, generally 80 to 100 degrees, and usually a hollow center. As the fuel entering the orifice is given a rotary motion by tangential holes the issuing fuel has both tangential and axial velocities. This results in low penetrating power and fairly uniform droplet size. As the injection pressure is raised spray droplet size decreases reducing the NO_X emission (Cipolat 2007).

The fuel injection system must be able to meter the desired amount of fuel, depending on engine speed and load, and inject the fuel at the correct time and with the desired rate. Further depending on the combustion chamber, the appropriate spray shape and structure must be produced. Usually, a feed pump draws the fuel from the fuel tank and carries it through a filter to the high-pressure injection pump. Depending on the area of application and engine size, pressures between 100-200 MPa are common (Heisler, 2003; Burman and Deluca 2000).

The high pressure injection pump carries the fuel through high-pressure pipes to the injection nozzles in the cylinder head. Excess fuel is transported back into the fuel tank. This rotating injector concept enhances the air-fuel mixing process and minimizes the local concentration of fuel, the injection direction of each spray will vary during the injection event. This is achieved by rotating the injector during injection. This type of fuel injection method will enhances mixture formation inside the cylinder, and will reduce the delay period of the combustion. RDI will help the formation of the homogeneous air fuel mixture inside the cylinder. As this avoids the local rich concentration of air fuel mixture, the NOx emission is minimized and the performance of the engine is improved (Abu Bakar 2008).

Replacement of conventional fuel injector by the RDI injector results in marginal increase in the HC, CO emission. It is evident that the HC, CO emissions can be controlled by using after treatment technique like catalytic converter and SCR. As such NO_X reduction techniques are complicated like water injection and EGR. Hence by utilizing the rotating injector technique the NO_X formation is controlled in the fuel combustion process.

In diesel engines air has a swirl motion inside the cylinder. Fuel is injected in narrow direction inside the cylinder, in case of multi hole nozzle injection spray having 120 degree gap between each spray (Coverdill *et al.,* 2008). The air gap takes more time to reach the fuel and mix with it and Ignite. Longer ignition delay is one of the reasons for an increase in the NO_X emission. Due to the rotation of the fuel injector during injection spray a co-swirl motion is created along with air swirl motion, it sprays the fuel throughout the cylinder during injection time itself. It helps reduce the ignition time and makes a homogeneous mixture inside the cylinder. This mixture reduce the peak combustion temperature. This reduction in peak temperature reduces the NO_X formation (Kern and Rolf 1999).

MATERIALS AND METHODS

The arrangement of the engine and experimental accessories are given Fig. 2.1

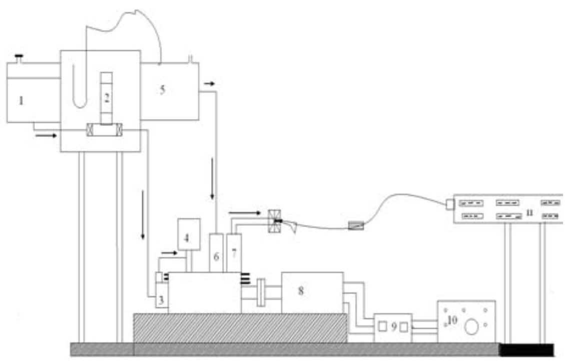

Fig 2.1: Experimental Set-Up

Table 1: Specification of the Engine

Engine Make	Kirloskar TAF-1
Number of Cylinder	1
Bore	87.5 mm
Stroke	110 mm
Compression Ratio	17.5:1
Brake Power	4.4 kW
Speed	1500 rpm
Type of Cooling	Air Cooling

Spcification of the test engine is given in Table.1.

1. Fuel Tank 2. Burette 3. Fuel Filter and Pump 4. Motor with Fuel Injector 5. Surge Tank 6.Intake Manifold 7. Exhaust Manifold 8. A.C. Generator 9. Ammeter and Voltmeter 10.Loading Rheostat 11.Exhaust Gas.

MODIFICATION OF FUEL INJECTOR

The existing injector is a stationary injector. To achieve the rotary motion of the injector modification of injection system is required.

Model of the outer sleeve

The outer sleeve is the main part of the rotating injector. The three dimensional model of the outer sleeve is shown in Fig. 3.1. It is modeled using CATIAV5R16 software.

The modified fuel injector consists of following parts.

- Outer Sleeve
- O-rings and oil seal
- Fuel Injector

Outer sleeve

The outer sleeve is a hollow cylindrical component made up of on steel. The inner side of the sleeve there are three grooves provided. These grooves are located at the top, middle and bottom of the inner portion of the sleeve. The top and the bottom grooves are called as O-ring grooves and the middle groove is called as the fuel supply groove. The three dimensional model of the outer sleeve is shown in Fig. 3.1.

The top and bottom grooves are used for locating the O-ring and, it guides the rotation of the injector and arrest leakage of the fuel the from fuel supply groove. The middle groove supplies fuel to the injector irrespective of angle position of the injector.

The fuel injector is located the inner side of the sleeve. The inner diameter of the sleeve is same as the injector body diameter. The outer middle section of the outer sleeve has collars with two drill holes. Collars are used for fixing the sleeve with the fuel injector in the cylinder head. Fig. 4.1 shows 3D representation of the outer sleeve.

O-Rings and Oil Seal

O-rings and oil grooves are used to withstand the fuel pressure inside the sleeve, protect from leakage of fuel and guide the rotation of the fuel injector. Three O-rings and one oil seal were used for this rotary operation. Two O-rings are located in the bottom side of the outer sleeve, one oil seal and O-ring located top of the outer sleeve. O-ring is made up of viton polymer it has inner diameter of 22 mm, 2 mm thickness and 24 mm outer diameter (Lawes 2002).

Fuel Injector

The fuel injector basically has two parts. The lower nozzle body and needle valve assembly, the upper injector body which contains the valve spring and preload adjustment device and which is normally a screw adjustment sleeve and capnut or simply a spacing shim (Abu Bakar 2008; Heisler 2003).

The spring thrust (compressive load) is transferred

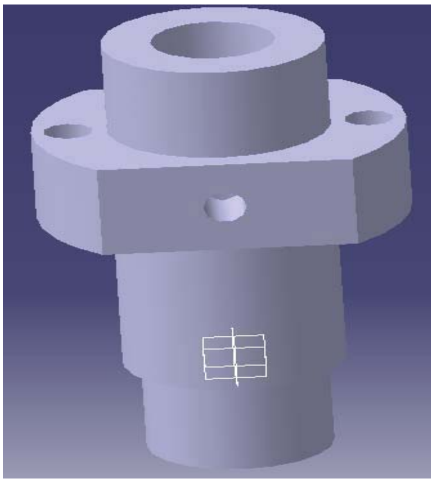

Fig. 3.1: Outer sleeve

Fig. 3.2 Modified Fuel Injector

to the needle valve via either a spindle with the high-mounted spring or with a spring plate for the low-mounted spring. Both halves of the injector unit, consisting of the upper injector body (holder) and the lower nozzle and needle valve assembly, are held rigidly together with a nozzle capnut.

The existing fuel injector is modified into a rotating injector, for which some modification is carried out on the nozzle body portion of the fuel injector. Around the body portion of the injector, single holes are made up to the fuel feed drill hole of the fuel injector. The diameter of the holes is 2 mm. These holes should match with the fuel supplying groove in the outer sleeve as shown in Fig. 6.1.

Modified Fuel Injector

A photographic view of the complete modified fuel injector is shown in Fig. 3.2. The fuel injector is inserted in the outer sleeve. The outer sleeve should be capable of withstanding the engine pressure and temperature of the engine. To avoid the downward movement of the injector due to fuel pressure C-lock is used on the sleeve. The injector body is coupled with a motor holding shaft motor to rotate the injector at 50 rpm clockwise. Rotation of the fuel injector is measured using a digital tachometer. The nozzle of the fuel injector is a three hole single cylinder kirloskar engine nozzle, but the existing fuel injector body is replaced with a Hino engine fuel injector body, drilled to 2 mm diameter up to the depth of the inner fuel orifice in the nozzle body for fuel flow from the outer sleeve fuel groove to the injector. This holes position matches with the outer sleeve inlet hole and the fuel supplying groove.

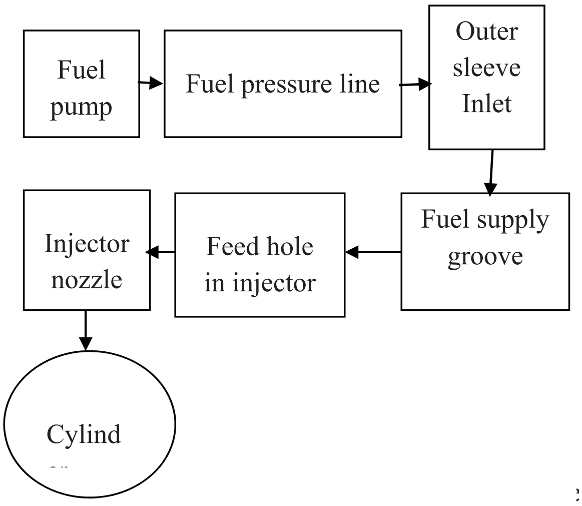

Fig 4.1: Fuel Flow Path Diagram

FUEL FLOW PATHWAY

The following flow diagram Fig. 4.1 shows the pathway of the fuel flow from the fuel pump to the cylinder through the rotating injector. In the fuel flow path the outer sleeve haves the major function of supplying the fuel to the injector. This outer sleeve accumulates some quantity of fuel and this accumulated fuel is supplied to the injector when it required.

The attachment of the rotating fuel injector is shown in Fig. 4.2. Experiments are conducted by using the above arrangement. Exhaust gas measurements are made by using a three gas analyzer.

SPRAY PATTERN

A typical diesel injection spray leaves each nozzle

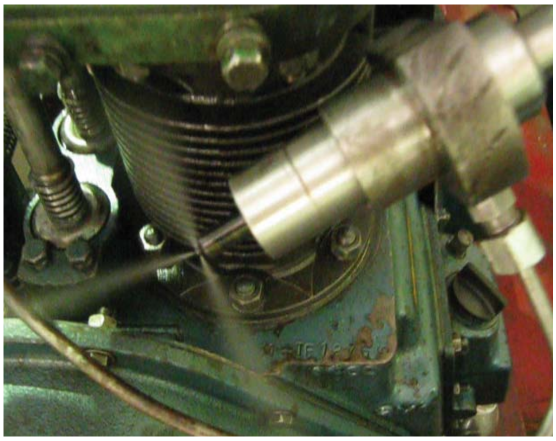

Fig. 5.1: Photographic View of Spray Pattern of the Conventional Injection

Fig. 4.2: Photographic View of Engine with Rotating Injector

hole with a narrow included angle, and develops a head vortex where the spray momentum is transferred to the compressed. Fig. 5.1 shows the spray pattern of the conventional fuel injection. Each successive element of fuel seems to pass through the head vortex of the previous element, to form a new head vertex further across the bowl until the combustion chamber wall is reached, or the injection is terminated. When the fuel is introduced into the combustion chamber as finely atomised sprays, the air entrainment increases by providing a mixture which is closer to the stroichiometric near centre of each spray (Hussein *et al.,* 2009; Boehman *et al.,* 2003). Critical pressure ratio cavitations in the nozzle hole occur which finely divide the fuel before it leaves the hole. In consequence the spray angle is larger and more air is entrained into the spray.

Spray Pattern of the Rotating Injection

The Rotating injector spray differs from the conventional spray. Due to the rotation of the injector, the spray is given a swirl motion (Buchner *et al.,* 2003). The above photographic view shows fine spray particles throughout the engine cylinder. Also it uniformly mixes with air. Fig. 5.2 shows the spray pattern of the rotating injector. Conventional injection spray has an air cone between each and every fuel cones, so it takes more time to mix with the air cone. This rotating injection spray collapses with air during injection itself, because mixture formation time is reduced. It may reduce the physical delay during combustion process. Higher delay period also one of the reasons for an increase NO_X emission. This rotating injection reduces the delay period and reduces the NO_X emission. This rotary motion of fuel spray issuing fuel has both tangential and axial velocities (Cipolat 2007). This results in with low penetrating power and fairly uniform droplet size. Although as the spray droplet size decreases slowly as the pressure is raised, it reduces the NO_X emission.

Fig. 5.2: Photographic view of Spray Pattern of the Rotating Injection

RESULTS AND DISCUSSION

Experiment were conducted by using conventional and rotating injector, The experiment results in terms of emission, performance and heat release rate are describe in this paper.

The combustion process in DI diesel engines is an unsteady heterogeneous three-dimensional process. Difficulties remain in quantitatively describing many of its critical individual processes (Burman and Deluca 2000). Yet, some models that exist today are able to approximate the combustion process and arrive at resultant emission levels that resemble those measured by the experiment.

The average distance between the droplets is expected to change with their location of the spray and it is greatest near the edge downstream from the centerline of the spray, where the smaller droplets are concentrated. The average local air fuel and, the combustion mechanism are expected to vary from one location to another (Heisler 2003)..

As one might expect, the local air fuel ratio is highest along the centerline of the spray and diminishes as move to the outer extremities of the spray cone. This air fuel ratio varies along the spray centerline. This distribution varies with the radial distance from the nozzle hole and takes into account all the fuel, both in the liquid and vapor phase. However, at the downstream edge of the spray and at distances further away from the core of the spray, one can assume that most of the droplets that are transported away from the core will be mostly or completely evaporated before the start of ignition, and that the mixture near the downstream edge of the spray consists of premixed fuel vapor and air.

HC, CO and CO_2 Emission

Rotation motion of the injector may make a leaner flame-out region. Near the outer edge of the spray, the mixture is often too lean to ignite or to support stable combustion. This region is referred to as the lean flame-out region (LFOR). With the LFOR, some fuel decomposition and partial oxidation products can be found. The decomposition products are mainly lighter hydrocarbon molecules (Coverdill *et al.,* 2009). The partial oxidation products include aldehydes and other oxygenates. It is believed that the LFOR is one of the major sources of unburned hydrocarbons as well as odorous constituent. The size of the LFOR depends on many factors, including the temperature and pressure in the chamber during the course of the combustion the air swirl and the type of fuel.

In general, higher temperatures and pressure extend the flames to leaner mixtures and thus reduce the LFOR size. Variation of HC and CO emissions with BMEP is shown in Fig. 6.1 and 6.2.

In the zone where the LFOR and LFR meet, primary combustion takes place where hydrocarbons react to form CO, H_2 and H_2O as well as various radical species as H, O, and OH. Other unburned hydrocarbons, having lower carbon number atoms than the initial fuel molecules, are formed (Padenb 2009). The rotating injection creates a bigger LFOR region because it emits more CO and HC emission. By increasing CO emission, CO_2 emission is reduced due to more lean flame out region, as shown in Fig. 6.3.

Reduction of NO_x Emission

After the ignition and combustion in the LFR, the flame propagates toward the core of the spray. In this region which is between the LFR and the core of the spray, the fuel droplets are larger. They gain heat by radiation from the already established flames and evaporate at a higher rate. The increase in temperature increases the rate of vapour diffusion, due to the increase in molecular diffusivity. These droplets may be completely or partially evaporated. If they are completely evaporated, the flame will burn all the mixture within the rich ignition limit. The droplets that are not completely evaporated may be surrounded by a diffusion type flame and burn as individual droplets or evaporate to form a fuel rich mixture. The combustion of this mixture depends on the aerodynamic factors that control the rate of mixing of the fuel and air rather than on the droplet parameter. Fig. 6.4 shows variation of NO_X emission with BMEP (Cipolat 2007).

The combustion in the spray core generally depends on local air fuel ratio, which is affected mainly by the interaction between the spray core and the swirling air. Under par-load operation, adequate oxygen is available and combustion is usually completed, resulting in NOx formation (Kern and Rolf 1999). The temperature of the flame front depends on both the local mixture temperature before the start of combustion

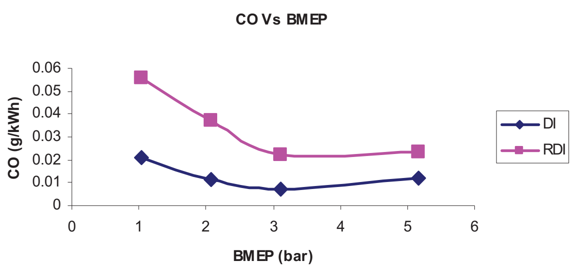

Fig. 6.1: Variation of CO with BMEP

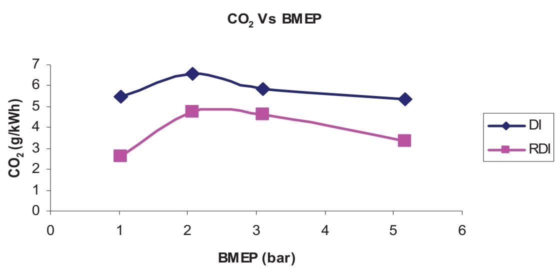

Fig. 6.3: Variation of CO2 with BMEP

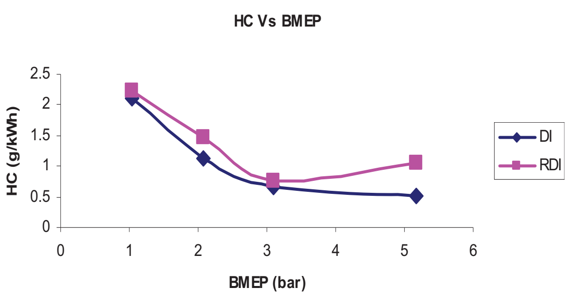

Fig. 6.2: Variation of HC with BMEP

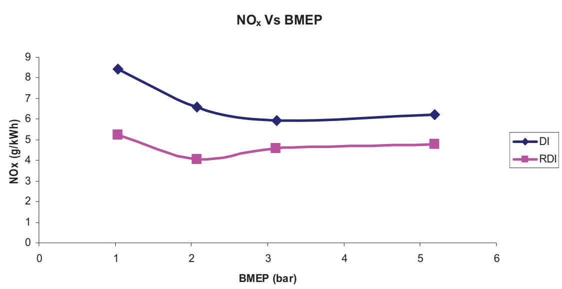

Fig. 6.4: Variation of NOX with BMEP

and the heat of combustion, which is partly a function of the concentration of the heavy compounds in the fuel used. The flame zone temperature is the major factor affecting NO_X formation.

The reduction of fuel air ratio to blow 0.02 would actually reduce NOx formation due to the drop in combustion temperature by air dilution. The increase in maximum combustion pressure, exhaust temperature, brake mean effective pressure and observed NO as the function of fuel-air ratio. Leaner fuel air ratio is achieved by using a rotating injector. The rotational injector creates radial and tangential motion of the spray inside the cylinder, which may be help to create a leaner fuel air ratio. Since peak combustion temperature and pressure are reduced, overall NOx emission is reduced.

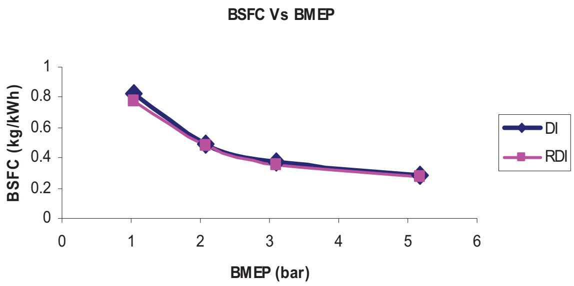

Fig. 6.5: Variation of BSFC with BMEP

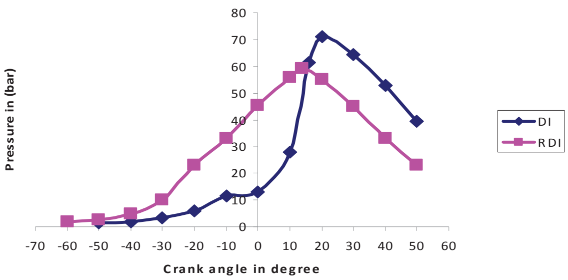

Fig. 6.6: Pressure-Crank Angle Diagram

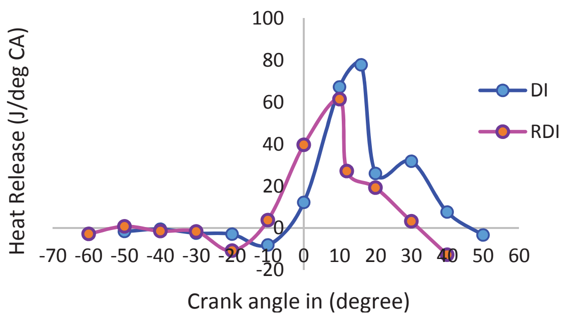

Fig. 6.7: Heat Release Rate

Fuel Consumption

The relationship between BSFC and BMEP is shown in Fig. 6.5.In the BSFC of the RDI system marginally less fuel is consumed from no load to full load. DI and RDI experiment is conducted by using the same diesel fuel and the same engine. But rotational speed of the experimental injector is 50 rpm. Calorific value of the fuel and engine speed are maintained in the same condition for both experiments because, almost uniform amount of fuel is consumed. Marginally less fuel is consumed in the RDI experiment compare than base experiment (Bae *et al.*, 2009).

Pressure Crank Angle Diagram

Peak cylinder pressure is the magnitude of maximum pressure developed due to the combustion of fuel by which chemical energy is converted into pressure energy. The magnitude and occurrence of peak pressure affects engine power and emissions. The rotating injection system starts to increase the pressure before the conventional injection system. As the rotating injection droplet size is small, it is ready to ignite a few degree in advance when compare to the conventional injection system. Also, it controls the peak pressure rise. Fig. 6.6 shows a typical pressure crank angle profile for the DI and RDI engine.

Conventional injection system produces higher peak combustion pressure around 70 bar. Rotating injection peak combustion pressure is 60 bar. It is less than that of the conventional injection system and also reduces peak combustion temperature.

Heat Release Rate

Heat release is zero during the compression process until shortly after the start of fuel injection. At this point, there is typically a slight negative dip in the curve due to the fuel vaporization and endothermic preflame reaction. When auto-ignition occurs, the heat release rate rises rapidly as the premixed fuel burns. The premixed combustion gives a characteristic spike to the heat release rate. The RDI engine starts to release the heat a few degrees of the crank angle before the conventional engine starts to release heat. Higher Peak temperature is a one of the reasons for increasing NO_X emission. In the case of rotating injection system less peak temperature is produced when compare to the DI system. It ensures the possibility of reducing NO_X

emission. A typical heat release rate profile for the DI and RDI engine has shown Fig. 6.7.

The diffusion of air and fuel mixture is promoted near the cylinder wall and the temperature of combustion gas is reduced to a low level so as to lower NO_X formation when compared to the conventional injection engine.

CONCLUSION

It is observed that the RDI engine shows a better performance and emission characteristics than the conventional fuel injector engine.

The following conclusions are achieved for the RDI engine over the conventional DI engine based on the experiment analysis.

- NO_X emission is decreased by 30% more than the conventional engine.
- Fuel consumption is marginally reduced.
- There is a considerable increase in HC and CO emission when compared to the conventional fuel injector engine.
- HC and CO emission can be controlled by after treatment techniques like SCR and TWC. Considerable NO_X emission can be controlled using the RDI injection method.

ACKNOWLEDGEMENTS

The authors wish to extend their gratitude to all who assisted in conductiong this work.

REFERENCES

Ahmad Hussein, Abdul Hamid, Rahim Atan, (2009) “Spray Characteristics of Jet-Swirl Nozzles for Thrust Chamber Injector”, Aerospace Science and Technology Vol.13 pp.192-196.

André Boehman, Juhun Song, Jim Szybist Mahabubul Alam, Ragini Acharya and Vince Zello, (2003) “Fuel Formulation Effects on Diesel Fuel Injection, Combustion, Emissions and Emission Control”, Proceedings of DOE Diesel Engine Emissions Reduction Conference August 24-28, Newport, RI.

Buchner.H, Merkle.K, Haessler.H, Zarzalis.N. (2003) “Effect of Co-and Counter-Swirl on the Isothermal Flow-and Mixture-Field of an Airblast Atomizer Nozzle”, International Journal of Heat and Fluid Flow Vol.24 pp.529-537.

Choong Bae, Essam Abo-serie, Seoksu Moon. (2009) “Air Flow and pressure inside a pressure-swirl Spray and Their Effects on Spray Development” Experimental Thermal and Fluid science Vol.33 pp 222-231.

Cipolat.D. (2007) “Analysis of Energy release and NOx Emissions of a CI Engine Fuelled on Diesel and DME” Applied Thermal Engineering Vol.27 pp. 2095-2103.

Coverdill. Robert.E, Chia-fon.F Tiegang Fang, White. Robert.A. (2008) “Effects of Injection Angles on Combustion Processes Using Multiple Injection Strategies in an HSDI Diesel Engine” Journal of Fuel Vol.87 pp.3232-3239.

Coverdill Robert.E, Chia-fon.F, Tiegang Fang, White. Robert A. (2009) “Air–Fuel Mixing and Combustion in a Small-bore Direct Injection Optically Accessible Diesel Engine Using a Retarded Single Injection Strategy” Journal of Fuel Vol.88 pp.2074-2082.

Dennis Konstanzer, Hans-Erik Angstrom, Magnus Sjoberg and Oskar Thorin, (1998) “The Rotating Injector, a New System for Diesel Combustion”, Society of Automotive Engineers Paper No. 982678.

Heinz Heisler, (2003) “Advanced Engine Technology”, Society of Automotive Engineers, pp.553-580.

Justin Robert Padenb, Maniarasanan.P, Nicholasc M.T. (2009) “Design and Performance Evaluation of Swirl Injectors for Water Evaporation at Low Pressure” Journal of Desalination Vol.235 pp.139-145.

Kang Kern.Y, Retiz Rolf. D (1999) “The Effect of Intake Valve Alignment on Swirl Generation in a DI Diesel Engine”, Experimental Thermal and Fluid Science Vol.20 pp. 94-103.

Keith Lawes, (2002) “The Rotating Cylinder Valve 4-Stroke Engine A Practical Alternative”, Society of Automotive Engineers, Paper No. 2002-32-1828.

Magnus Sjoberg, (1999) “In-Cylinder Soot-Control with High-Speed Rotating Injector for DI Diesel Engines”, Society of Automotive Engineers Paper No. 1999-01-3489.

Magnus Sjoberg. (2000) “Rotating Injector for DI Diesel Engines Analysis of the Combustion System with Regards to Swirl, Fuel, Boost and Fuel/Air-Equivalence Ratio” Society of Automotive Engineers Paper No. 2000-01-0229.

Paul G.Burman, Frank Deluca, (2000) “Fuel Injection and Controls for Internal combustion Engines”, Society of Automotive Engineers, pp.110-137.

Rosli Abu Bakar, Semin and Abdul Rahim Ismail, (2008) “Fuel Injection Pressure Effect on Performance of Direct Injection Diesel Engines Based on Experiment”, American Journal of Applied Sciences Vol.5 pp.197-202.