Operation and Developments of DISI Engines – A Review

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Abstract- In this paper an attempt has been made to review the operation and developments of Direct Injection Spark Ignited (DISI) Engines. Though the name DISI has been attributed to Mazda’s engine of 2005, the direct injection has been used since 1902. Throughout the paper Gasoline direct injection and DISI have been used interchangeably. The DISI engines have advantages of both direct injection of compression ignited engines and homogeneous combustion of spark ignited internal combustion (IC) engines. The power output is high with efficient fuel economy. The fuel economy is maintained over all the variety of loads including low and medium loads. The torque produced with DISI engines is far ahead of that of spark ignited, compression ignited and any other forms of IC engines. Different forms of DISI engines with different number of cylinders, different alignment, different injection timing, different combustion timing, etc. are implemented on different vehicles. Only few of them are suited to specific applications. In this paper the operation, advantages and development of DISI engines are presented.

Keywords – Gasoline direct injection, DISI, Mazda, low load, SFC

I. INTRODUCTION

The purpose of automobile industry is to provide basic transportation facility while the goal is to provide a high power, low specific fuel consumption, low noise, better driving comfort and low emissions. The air pollution created by this field is becoming more important these days as the number of vehicles on road increased. The governmental and ecosystem safety agencies are updating the emission limits every year. Also, incessantly raising cost of fuel mandates improvement of thermal efficiency of the engine. As the carburetor based engines cannot maintain the air-fuel ratio close to the stoichiometric value at different load conditions, a catalytic converter can’t be used. Hence these engines suffer from high emissions and have low thermal efficiency. Port based engines are used since 1980s. In these systems, the induced air can be measured accurately and the fuel is injected precisely to maintain certain air-fuel ratio. The following are the advantages of port based engines compared to the carburetor based engines.

- Less & controlled emissions
- High volumetric efficiency resulting in high output power and torque
- Less specific fuel consumption
- Quick engine response to throttling
- Noise decreases [1][2]

Though the port based engines have the above advantages, these engines cannot meet the increasing demands of performance, emission and fuel budget of today [3]. The use and implementation of electronic controlled direct injection spark ignited (DISI) engines was stared since early 1990s. The direct injection spark ignited engines have the following features.

- High accuracy of air-fuel ratio
- Less throttling losses
- High thermal efficiency
- High compression ratio
- Less fuel consumption and low COx emissions
- Less heat losses
- High performance and high volumetric efficiency
- Good cold-start performance
- Good drive comfort [4][5][6]

The compression ratio and air-fuel ratio have a significant effect on the engine’s efficiency. In DISI, because of high compression ratio, the power output and fuel consumption reduces. The highest efficiency or the lowest fuel consumption occurs with a weaker mixture than the stoichiometric [7]. Since the port based engines work at stoichiometric ratio, almost it is impossible to have enhancement in fuel consumption. The compression ratio is about 9 to 10 in these engines. To avoid the knock, the compression ratio can’t be increased ahead of this value. With equal engine volume, the increasing volumetric efficiency raises the engine power output. The DISI engine works with a lean mixture and un-throttled at lighter loads, this provides improvements in fuel economy. At full load, as the DISI engine works with almost homogeneous charge and slightly rich mixture, the engine gives good output power [8]. Here fuel is injected into the cylinder before the ignition when load is low or medium. In this case, the air fuel ratio is heterogeneous throughout the cylinder, usually, the mixture is rich in front of the injector and it is lean in other places. In homogeneous operation, fuel will be injected during the intake stroke [9][10].

The injected fuel will evaporate in the cylinder. This evaporation cools the intake charge permitting high compression ratio thereby higher volumetric efficiency which ultimately results in high torque [11]. The compression ratio that can be obtained with DISI engines is 12 [12]. The knock, in DISI engines, usually will not occur as air alone is compressed at low and medium loads. At full loads, as the fuel is injected into the cylinder, the charge developed cools the air and hence the knocking tendency will be decreased. As the vehicles are utilized more in urban areas, studies on improving the fuel efficiency in urban driving are improving. Usually vehicles run at part loads in short runs and in urban driving. Volumetric efficiency is less with part loads; hence the effective compression ratio decreases resulting in less thermal efficiency and higher fuel consumption.

The urban driving fuel economy of vehicles is very high [13]. Because, major part of the life of a vehicle faces urban traffic, owners of the vehicles prefer low fuel consumption at urban traffic. At full load, as the DISI engine operate with throttle, only a small saving of fuel can be obtained compared to port based engines. But a potential decrease of fuel requirement at part load was made practical with DISI engines. The improvement in the engine efficiency is obtained as an outcome of decreased pumping losses, high compression ratio and further extension of lean operating limit under stratified combustion conditions at part engine loads. With DISI engines, it is observed that around 20% decrement in fuel consumption and 10% improvement in power output compared to traditional port based engines was achieved[14]. Though, the DISI engines offer more efficiency and more power, it too has some limitations. Over the time of use, a carbon build-up occurs in the intake valves. This carbon build-up reduces the air flow into the cylinder; hence the total power output reduces. It can also cause sporadic ignition failures [15][16].

II. OPERATION OF DISI ENGINES

In the carburetor and port based engines it is prepared in out-cylinder. In DISI engines the mixture is prepared in-cylinder. The three cases are shown in figure 1.
Figure 1. Air-fuel mixture preparation in the gasoline engines

In DISI engines during the induction stroke, air alone flows from the intake valve. This ensures better control of injection process and then injection of fuel takes place late during the compression stroke, where the intake valves are closed [17]. The advantage in port based engine lies in the intake system which acts as a pre-vaporizing chamber [18]. In DISI engines, because of lack of time for fuel to vaporize, the fuel is injected at high pressure to help the vaporization and atomization process. The duration of injection is very less. Advanced injecting timing causes piston wetting. Retarded injection timing decrease the time for air-fuel ratio [19].

In port based engines, a liquid layer is formed in the intake port causing delayed fuel vaporization. Particularly in cold weather conditions it is required to raise the fuel quantity for best mixture. This high part of fuel causes increasing emissions during winter. These high emissions can be avoided if the fuel was directly injected into the combustion chamber and during cold season more fuel can be pumped directly into the chamber [20]. The DISI engines are implemented in two basic charge modes. One is stratified and other homogeneous charge mode. The stratified charge is used at partial loads. In this case the fuel is injected in the compression stroke which supplies the stratified charge. The engine can be made to operate at an air-fuel ratio exceeding 100 and fully un-throttling operation is possible, as engine is throttled the air-fuel ratio is controlled in the range between 30 and 40.

At full load condition a homogeneous charge is chosen. In this case the fuel is injected during intake stroke so that chance of forming homogeneous mixture increases. Almost throughout this mode, the mixture is slightly rich with air-fuel ratio in the range 20 to 25 [21]. In homogeneous charge condition the managing of engine load is by throttling while in stratified charge condition it is by air-fuel equivalence ratio [8]. Figure 2 shows the homogeneous and stratified charge modes. In stratified mode, three combustion processes are used to form ignitable mixture. These are spray guided, wall guided and air guided combustion processes as shown in figure 3.

The above three processes are based on the method with which the fuel is sprayed and the way in which the fuel is transported near the spark plug [23].

Spray guided combustion process: Here the fuel is injected near the spark plug where it evaporates. The spray guided combustion theoretically has highest efficiency. This process requires advanced injection systems. The spray guided combustion has the following advantages. These include less wall wetting, large stratified operation region, reduced emissions, and less sensitive to cylinder to cylinder variation and in-cylinder air flow. Recognized limitations include high sensitivity to changes in injection and ignition timing and spark plug reliability [24]. Mercedes-Benz devised a sophisticated spray guided combustion system. It is a stratified charged gasoline injection (CGI) engine with piezo injection technology. The spray guided injection achieves better efficiency than the conventional wall guided injection process. The advantage of CGI engine is attained at the stratified operating mode. In this mode the engine runs with excess air hence high fuel efficiency is obtained. High rpm and higher loads can be driven using multiple injections. During each and every compression stroke a series of injections takes place space a fraction of seconds apart. This permits good mixture formation, good combustion and low fuel consumption [25].
Wall guided combustion process: In this case a specially designed piston will be used to transfer the fuel to the spark plug. The fuel will not evaporate completely because the fuel is injected on the surface of the piston resulting in high emissions and fuel consumption. Usually this system will be used along with air guided combustion process.

Air guided combustion process: The fuel is injected onto the flow of air which moves the fuel sprayed near the spark plug. With a special shape the inlet ports provide the air flow and the speed of the air is controlled using air perplexes in the manifold. Here the fuel does not wet the piston and the cylinder. Most of the CGI DISI engines use a large scale air motion as well as specially shaped piston to keep the fuel spray compact and to move it to the spark plug [26]. In air guided and wall guided combustion systems the injector is isolated to the spark plug. Volkswagen DISI system is a combination of two systems. The resulting system is less sensitive against the cyclic variations of airflow. As shown in figure 4, injector is placed intake-side. The fuel is injected into the chamber but onto the piston with a specific angle. Piston has two bowls; fuel bowl and air bowl. The fuel bowl is on the intake valve side and air bowl is on the exhaust valve side. Tumble or swirl flow is obtained by special shaped intake port [22]. The fuel is guided simultaneously via air and fuel bowl to spark plug.
III. DEVELOPMENTS

The DISI engine was invented by Leon Levavasseur in 1902, who is the inventor of V8 engine. The first model of DISI engine was the Hesselman engine invented by Jonas Hesselman in 1925 [28][29]. Hesselman machines utilized the ultra-lean burn principle and fuel was injected at the end of compression stroke and then ignited with a spark plug. Direct injection was applied during Second World War to almost all high output production aircraft power plants made in Germany, the Soviet Union and the US.

In 1952, the first automotive DI system was run on gasoline which was developed by Bosch and was introduced by Goliath and Gutbrod. It was a high pressure diesel DI pumps with a setup of intake throttle valve. The first production sports car to use DI is Mercedes-Benz 300SL in 1955. The Bosch injectors were placed into the bores on the cylinder wall used by the spark plugs in other Mercedes-Benz six cylinder engines. In early 1970s research was conducted by American Motors Corporation to develop a Straticharge Fuel-Injection system [30]. The AMC straight-6 engine was modified with a redesigned cylinder head. It incorporated a mechanical device that automatically responds to the airflow of the engine and loading conditions. The prototype engine was road tested using a 1973 AMC Hornet and resulted in teething problems of mechanical fuel controls.

In the late 1970s a stratified charge engine was developed by the Ford Motor Company. It was called PROCO for programmed combustion [31][32]. It had used a unique high pressure pump and direct injectors. The practical problems faced with this engine include electronic controls, pump and injector costs, and lean combustion produced NOx in excess of limits. The period from early 1980s to 1995 had no improvements in the design of DISI engines. In 1996, a DISI engine came into the picture again in the form of Mitsubishi in Japan. The engine is Galant/Legnum’s 4G93 1. L inline – four [33][34]. This was again a failure one due to high emission and poor fuel efficiency [35]. In 1997 Nissan came with Leopard with VQ30DD which works with direct injection [36].

In 1998 the Toyota’s D4 DI system equipped with SZ and NZ engines appeared on Japanese market vehicles [37][38][39]. The Toyota’s 2GR-FSE V6 uses a more advances DI system with both direct and indirect injection using two injectors [40]. In 1999, Renault introduced 2.0 IDE which uses high ratios of exhaust gas recirculation instead of lean burn approach to reduce the fuel consumption at low engine loads, with DI allowing the fuel to be concentrated around the spark [41]. Later on DISI engines have been tuned for their high fuel efficiency and high performance. Hyundai, Volvo and Peugeot Citroen entered into development of Mitsubishi’s gasoline direct injection technology [42]-[46]. In 2000, Volkswagen announced its DISI engine Volkswagen Lupo [47]. The technology was taken from Audi’s Le Mans prototype race car R8.

In 2002, Alfa Romeo 156 with DISI engine the Jet Thrust Stoichiometric went for sale [48]. In 2003, Ford introduced a 1.8L Duratec SCi naturally aspirated engine for the Mondeo [49]. In the same year, BMW introduced a low pressure DISI N73 V12 [50]. This initial setup could not enter lean-burn mode. Then BMW released its next generation high pressure injection system in 2006 [51]. In the same year, General Motors introduced a 155HP 2.2L Ecotec for the Opel and Signum. In 2004, Isuzu released the DISI engine which was used on 2004 Axiom and 2004 Rodeo. Isuzu claimed the benefit of DISI that the vaporizing fuel has a cooling effect permitting high compression ratio that raises output power.
In 2005, Mazda started to use the Mazdaspeed6 and the new Mazdaspeed3. In 2006, BMW introduced the N54 twin turbo charged DI inline-six engine for 335i Coupe, 335i Sedan, 535i series and 135i models [52]. In the same year, Mercedes-Benz introduced its DI system on the CLS 350 CGI with common rail, peizo-electric direct fuel injector [53]. In the same year Audi released V8 engine with FSI technology that can produce BHP with low carbon emission and more fuel economy. In 2007, General Motors introduced the 3.6L V6 LTT SID for the Cadillac CTS and ST. In the same year Ford released EcoBoost for a range of vehicles [54]. In 2008, BMW released X6 xDrive50i with DI twin turbo N63 engine [55].

In 2009, Ferrari released the front engine California with DI system [56]. Proscche and Jaguar also released their DI engines [57]. In 2010, Infiniti released M56 with DI. In 2011 Hyundai Sonata model came with DISI [58]. In 2013 the Acura RLX came with DI which became the first Honda GDI. In 2014, GM LT1, a 6.2L V8 used DI, VVT and variable displacement. The 2014 Hyundai Accent features an aluminum block 138 14 GDI engine. Since the inception of GDI or DISI engines, the focus is on improving the combustion characteristics of the engines. This can be done possibly by injecting the fuel with high pressure and directing the fuel to mix or interact with the air rapidly in short time. Specialized injector may be required for this purpose.

IV. CONCLUSIONS

The direct injection spark ignition engines with its fuel efficiency and high output power outperform most of the other engines of today. The emissions, fuel consumption are less and torque produced, output power, efficiency are high. The attractive feature of it mainly lies in the low and medium load fuel economy and emission levels. All is because of homogeneous combustion at full load and stratified charge operation at low and medium loads. The homogeneous combustion at full load is only nominal it is not complete homogeneous. The stratified charge operation is similar to that of compression ignition engine. At low and medium loads the fuel consumption and emission levels depends on the grade of combustion. If the homogeneity of the combustion improved optimum fuel consumption and emission levels can be obtained. Homogeneous combustion may be obtained by using a special kind of injectors to spray the fuel with high pressure with different angles and velocities.

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