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A STUDY OF DIESEL AND BIO-DIESEL FUELS DEPOSIT FORMATION DUE TO FUEL SPRAY IMPINGEMENT

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ABSTRACT

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(Keywords: Fuel spray, fuel deposit, diesel, bio-diesel)

The formation of fuel deposits investigation is important to solve problems that involve with deposits in an engine. The problems become significant when bio-diesel fuel is used due to its higher density and T90 values compare to the typical diesel fuel. Fuel spray deposition test was conducted for diesel fuel (DF), palm oil based methyl ester bio-diesel fuels (B100) and bio-blended diesel fuel (B5, B10, B20) by using Manual Fuel Spray Apparatus (MFSA). DF, B5, B10, B20 and B100 sprays were impinged on a hot surface which has a surface temperature of 357°C at spray interval of 1 minute and 2 minutes. Every 10 spray repetitions, amount of deposit accumulated was measured. Maximum number of fuel spray for the deposition test was at 100 fuel sprays. Comparison of deposit formation tendencies was made for all tested fuels. Amount of deposit accumulated for the fuel spray deposition were increased with the percentage of bio-diesel content in fuels. DF obtained lowest deposit development rate and lesser amount of deposit accumulated. However, B100 accumulated greatest amount of deposits compared to others. In term of deposit development rate, bio-diesel fuel and bio-blended diesel fuel have similar deposit development rate. It was found that, longer spray interval caused reduction of deposit development rate and amount of deposit accumulated at initial stage and final stage of deposition for diesel, bio-diesel and its blends. The fuel spray deposit formation in this study is depending on fuel spray interval, types of fuel, spray angle, deposit development rate, amount of deposit at initial stage of the deposition and the maximum evaporation rate point (MEP) of fuels.

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ASTM	American Society of Testing and Materials
B10	10% Bio-Diesel Fuel Blends With 90% Diesel Fuel
B100	100% Palm Oil Based Methyl Ester Bio-Diesel Fuel
B20	20% Bio-Diesel Fuel Blends With 80% Diesel Fuel
B5	5% Bio-Diesel Fuel Blends With 95% Diesel Fuel
CCDI	Combustion Chamber Deposit Interference
CI	Compression Ignition
CN	Cetane Number
CO	Carbon Monoxide
CP	Cloud Point
DF	Diesel Fuel
DI	Direct Injection
FSCT	Fuel Spray Characteristics Test
FSDT	Fuel Spray Deposition Test
HC	Hydrocarbons
HHV	Higher Heating Value
IDI	In-Direct Injection
MEP	Maximum Evaporation Point
MFSA	Manual Fuel Spray Deposition Test
N_2O	Dinitrogen Oxide
NO_X	Nitrogen Oxides
OHC	Over Head-Cam
ORI	Octane Requirement Increase

PM	Particulate Matters
PP	Pour Point
SO_2	Sulphur Dioxides
SO_X	Sulphur Oxides
THC	Total hydrocarbon
US EPA	United States Environmental Protection Agency

Nomenclature

A_D	Deposit Development Rate Factor Based on the Deposition	
A_R	Deposit Development Rate Factor Based on the Relative	
B_D	Initial Deposit Factor Based on the Deposition Mass	[g]
B_R	Initial Deposit Factor Based on the Relative Deposition Mass	[g]
	Deposition Mass	[$spray^{-1}$]
D_x	Theoretical Coverage	[mm]
D_y	Spray Distance	[mm]
	Mass	[g/spray]
M_R	Mass of Deposit Remain on a Hot Surface	[g]
M_S	Average Mass of Deposit a Single Fuel Spray	[g]
N_S	Number of Fuel Sprays	[spray]

Greek Letters

ρ	Fuel Density	[kg/m^3]
θ	Fuel Spray Angle	[°]
ϕ	Injector Diameter	[mm]
τ_S	Fuel Spray Interval	[min]

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Chapter 1

INTRODUCTION

1.1 Background

Investigations on deposits in engines for gasoline and diesel fuels were conducted more than 40 years ago. Many investigations have been conducted in order to understand the deposit effects on engines and how these deposits develop in engines. It was found that deposits in combustion chambers can form through three different types of formation process: (1) through condensation of unburned gases on cooler walls in combustion chambers; (2) through impingement of unburned fuel droplets on walls; and, (3) through fuel flow on walls such as on intake valves, on injector tips and in injector holes.

1.2 Fuel Deposit Investigation

Generally, there are three main investigations on deposits which are now still continuing due to various types of engines that are available and also due to new developments in engine technology. The investigations cover (1) the effects of deposits on engines; (2) the factors that cause the deposit formation; and, (3) the investigation of deposit properties. The effects of deposits on engines are including emissions, heat loss, engine performance and engine damage. However, the factors effecting deposit formation, such as fuel and oil, engine operating conditions, wall temperatures, and air/fuel ratios, are still being investigated for various types of engines. Deposit properties were also investigated in order to learn more about thermal properties and its structures. This last investigation is related to and effects the first two investigations mentioned above. The porosity of deposits is closely related to emissions and heat loss. Further, deposit structure and composition determine the wear that causes engine damage. As a result of these studies, deposit mechanisms and deposit formation preventive measures in engines have been suggested.

Most deposit research available in the literature was conducted by using real engine tests. Real engine test can be categorized into two types. Those using engine bench tests and those using vehicle tests. Both tests require long periods and traveling long distances, respectively. Some deposit investigations for engine bench tests required up to approximately 200 hours of engine operation **[1-3]**. Others, such as Hutchings, et. al. **[4]** conduct investigations on deposit control by using a new lower-emission engine test with 360 hours of engine operation. In terms of deposit investigation through vehicle tests, long distance travel is required to obtain a significant amount of deposit and effects for certain investigation. Tarkowski, et. al. **[5]** conducted an investigation to determine the influence of fuel oils on the deposit composition in a diesel engine combustion chamber, where the investigation required 70,000 km of travel distance. Due to long periods and long travel distance, both types of test involved high operating costs and were exposed to engine damage during the deposition test.

1.3 Factors of Deposit Formation

The deposit formation in an engine appears to depend on a combination of different parameters, such as fuel, surface material, temperature, pressure, combustion chamber environment, etc. However, wall temperature is one of the most important parameters that effect the deposit formation. Jonkers, et. al. **[6]** mentioned the effect of different operating parameters on deposit formation such as engine load, power output, surface temperature, coolant temperature and injection timing. No specific conclusion can be made for each type of parameter in explaining the deposit formation. For each parameter, deposits could be increased or decreased depending on the interaction between other parameters of the engine in effecting the deposit formation, where the interaction might be different for different types of engines. Due to the many factors and parameters effecting the deposit formation in an engine, it is considered a complex process. Because deposit formation is caused by such complicated phenomena, there are few cases of research available on the detail mechanisms involved.

1.4 Deposit Formation Mechanism

In order to understand the mechanism of engine deposit formation and to find more effective solutions for deposit reduction, both real engine and fundamental studies on engine deposits are significant. Fundamental studies on deposit formation are very important. Extensive studies have been done on the evaporation of fuel, especially single and bi-component fuels **[7-13]** and also on actual multi-component fuels **[14, 15]** that can serve as part of the fundamental knowledge in deposit formation.

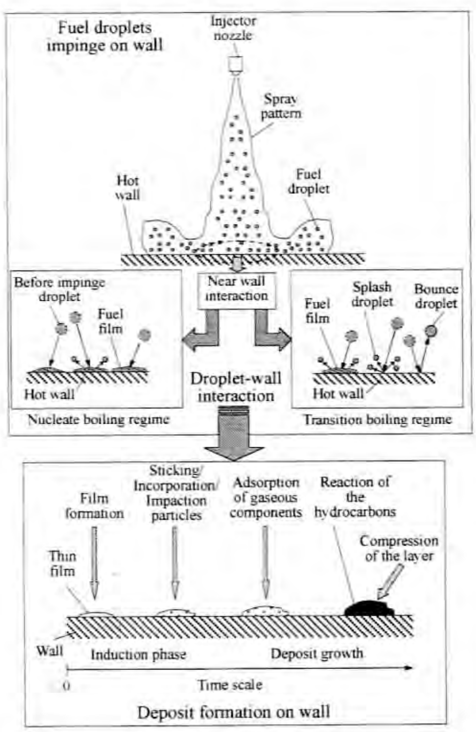

Figure 1-1 Deposit Formation Mechanism in an Engine

In real engines, a great number of fuel droplets are involved during atomization. The droplets evaporate and burn in the combustion chamber space. However, some of the droplets find their way to impinge the wall surface in the combustion chamber as illustrated in **Figure 1-1**. The interaction between fuel spray and a surface within an engine lead to the deposition of liquid fuel films **[16]**. This liquid film formation is one of the factors that caused deposit formation on the wall surface in the combustion chamber.

1.5 The Effect of Fuel Spray Impingement on Deposit Formation

In some cases for diesel engines, fuel spray impingement on a hot wall surface in a combustion chamber cannot be avoided. For example, in a small bore DI diesel engine, at high load engine operation, more than 50 percent of the fuel impinged upon the piston bowl as observed by Werlberger and Cartellieri **[17]**. The tendencies of fuel spray impingement with a hot wall surface in an engine increase due to following reasons:

1) Higher injection pressure that increased spray penetration and also when the spray impingement was used as a design consideration to promote spray atomization **[18]**.
2) Engine operation with longer ignition delay compared to the injection period **[19]**.
3) Engines that have a short distance between the injection nozzle and the piston head such as for small and high speed engines **[20]**.
4) Unburned fuel droplets resulting from incomplete combustion (such as for bio-diesel fuels) **[21]**.

As fuel spray impinges on the wall surface in an engine, liquid fuel film forms on the surface. The amount of fuel film that adhered on the wall depends on the wall surface temperature. The wall temperature will determine the amount of non-volatile or heavy molecular weight fuel components that remains on the wall and also the droplet-surface interaction during spray impingement. Probably, less liquid film adhered on the wall for high surface temperatures and also when the interaction is within the transition boiling regime. Within this regime, more droplets will bounce as secondary droplets to be impinged on the other surface areas in the combustion chamber or emitted from the engine during the exhaust stroke. The liquid fuel film that adhered and remained on the wall surface will further experience physical (evaporation, impaction of particle, etc.) and chemical (thermal decomposition, polymerization, etc.) processes due to the hot wall surface temperature. This results in deposit development on the wall surface in the combustion chamber as illustrated in **Figure 1-1**.

1.6 Deposit Removal Mechanism

During the combustion process, the deposit formation, especially carbonaceous deposit formation, is more severe due to high temperature gases and flames that increase the carbonization process. Furthermore, the attachment of soot particles also occurs during the process. In a real engine, high gas temperature and flames caused part of the deposits on the wall surface to burn and oxidize rapidly, resulting in deposit reduction. The reduction of deposits in an engine can also be caused by other factors, such as gas flow, piston movement and vibration, where part of the deposit is removed physically and emitted from the engine during the exhaust stroke of the engine. The next spray impingement will impinge on the deposit layer surface that formed from the previous impingement. The deposit formation processes as mentioned above repeat until the end of engine operation. During engine operation, the deposit layers also piled-up and covered the wall surface of the combustion chamber. However, in a real engine, after a certain period of time, the amount of deposit accumulated on the surface will stabilize, where the rate of deposit formation and the rate of deposit removal reach an equilibrium state.

1.7 Simplified Test for Bio-diesel Fuel Deposit Investigation

Deposit formation in an engine is a complex phenomenon and it is difficult to observe deposit development and its mechanisms in a real engine. Thus, a simplified method known as a fuel spray deposition test was proposed in this study. The basic concept of this simplified method is the repetition of fuel spray on a hot surface resulting in the piled-up deposit layer process on the wall surface.

Bio-diesel presents a lucrative alternative, particularly for compression ignition engines, because it is a renewable energy source that can be used in these engines without significant changes in their design [22]. Performance and emission characteristics of compression ignition engines depend strongly on inner nozzle flow and spray behavior. These processes control the fuel air mixing, which in turn is critical for the combustion process. The differences in the physical properties of diesel and biodiesel are expected to significantly alter the inner nozzle flow and spray structure and, thus, the performance and emission characteristics of the engine.

The main purpose of this research is to study diesel and bio-diesel fuel deposition in an engine by using fuel spray deposition test. Deposit development on a hot surface due to fuel spray impingement is to be observed. The fuels used in this study are bio-diesel fuel and diesel fuel.

In this study, there are three major scopes needs to be considered in order to achieve the objectives of study. The first one is to design and fabricate test rig for the experiment. Then investigate the fuel spray deposition on a hot surface for different type of fuel. Last but not least is to investigate the effect of spray interval on the fuel deposition.

Chapter 2

LITERATURE REVIEW

2.1 Background of Diesel Engines

Although a diesel engine and gasoline engine operate with similar components, a diesel engine, when compared to a gasoline engine of equal horsepower, is heavier due to stronger, heavier materials used to withstand the greater dynamic forces from the higher combustion pressures present in the diesel engine.

The greater combustion pressure is the result of the higher compression ratio used by diesel engines. The compression ratio is a measure of how much the engine compresses the gasses in the engine's cylinder. In a gasoline engine the compression ratio (which controls the compression temperature) is limited by the air-fuel mixture entering the cylinders. The lower ignition temperature of gasoline will cause it to ignite (burn) at a compression ratio of less than 10:1. The average car has a 7:1 compression ratio. In a diesel engine, compression ratios ranging from 14:1 to as high as 24:1 are commonly used. The higher compression ratios are possible because only air is compressed, and then the fuel is injected. This is one of the factors that allow the diesel engine to be so efficient.

2.2 Diesel Fuel Injection System

The diesel fuel injection system has undergone many changes over the years. Previously, cars used to have a carburetor installed in them, but such cars are no longer on the market. Now, almost all vehicles will supply are fuel using injection systems.

The fuel injection system is a vital part of the diesel engine. This system pressurizes and injects the fuel. In this way the fuel is forced into air, which has been compressed to high pressure in the combustion chamber.

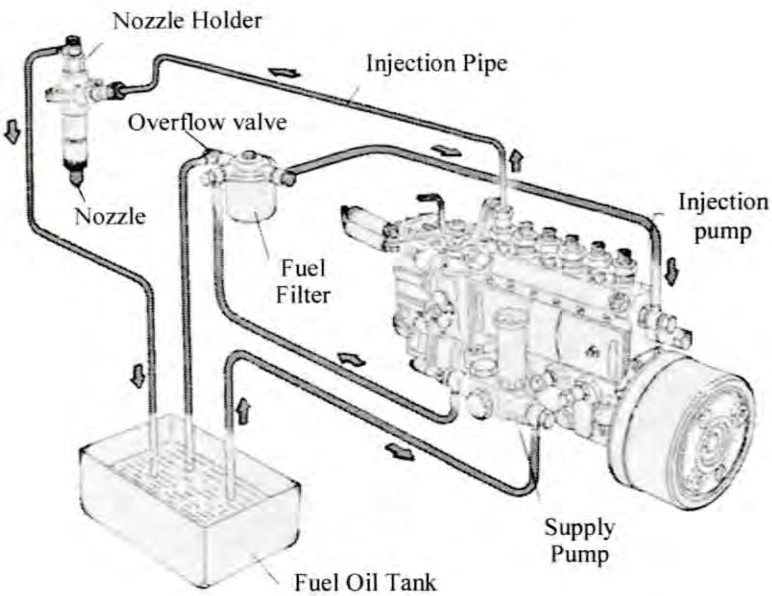

Figure 2-1 Diesel Fuel Injection System

The diesel fuel injection system that showed in **Figure 2-1** consists of a fuel injection pump, an injection nozzle, a feed pump, a fuel filter and a high-pressure pipe. The fuel injection pump pressurizes fuel to high pressure and then sends it via the high-pressure pipe to the injection nozzle, which injects the fuel into the cylinder.

2.2.1 Type of Injection System

There are two types of diesel injection system such as indirect-injection (IDI) and direct injection (DI) system. The indirect-injection (IDI) injects the fuel into a small pre-chamber between the injector and the cylinder such in **Figure 2-2**. IDI engines typically operate at higher compression ratios, in a range of 20:1 to 24:1. The piston head does not have a hollow, and the air in the pre-combustion chamber gets compressed and heated.

The fuel is sprayed by a single-port, pin-type injection nozzle into a pre-combustion chamber.

IDI systems create a more rapid mixing of the fuel and air. There are, however, some drawbacks. IDI systems lose more heat during compression. This is why IDI engines have higher compression ratios to reach the necessary air temperature. This usually results in fuel economy that is significantly lower than a DI engine. IDI engines may also be hard to start, which is why glow plugs are installed in the pre-chamber.

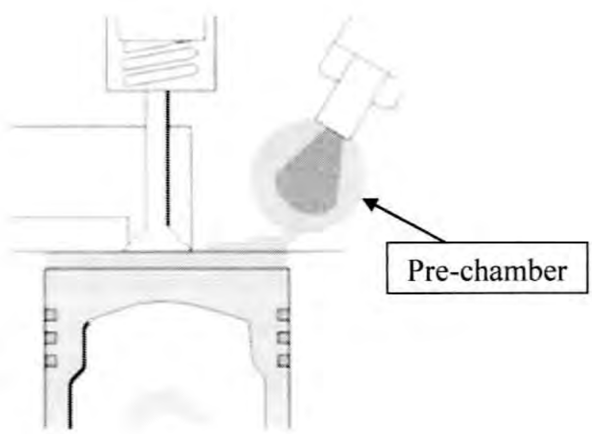

Figure 2-2 Indirect-Injection System

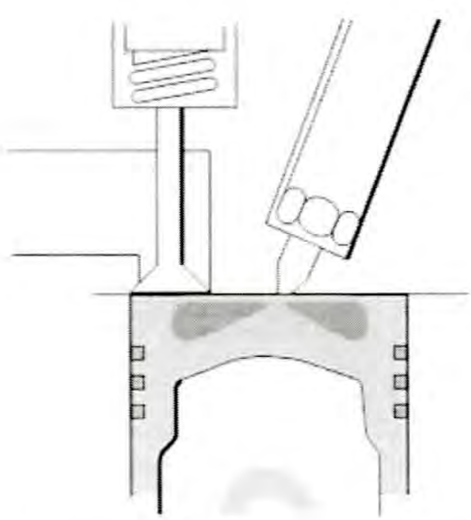

Figure 2-3 Direct-Injection System

In a direct-injection (DI) system, the fuel is introduced directly into the cylinder. DI engines usually have compression ratios in the range of 15:1 to 18:1. Fuel is injected through a multiport injector nozzle into the piston hollow that showed in **Figure 2-3**, mixes with the compressed air, and combusts. Direct injection injectors are mounted in the top of the combustion chamber. The problem with these vehicles was the harsh noise that they made. Fuel consumption was about 15 to 20 percent lower than indirect injection diesels.

Among direct injection systems, there are several design options as showed as **Figure 2-4**. These include the radial distributor injection system, the common rail system, the unit injector system and the unit-pump system **[23]**. These systems are describe as below.

(A) Radial injection system

Figure 2-4(A) showed the distributor injection systems are typically found in passenger cars and light- to medium-duty trucks. Distributor injection systems for direct injection systems reach an injection nozzle pressure of up to 1,950 bar. These systems may be mechanically controlled or electronically controlled **[23]** .

(B) Common rail system

In common rail systems such in **Figure 2-4(B)**, the separate pulsing high pressure fuel line to each cylinder's injector is eliminated. The common rail system's distinguishing feature is that the injection pressure is independent of engine speed and the volume of injected fuel. Pressure is generated by a high-pressure pump. The type of pump and control system varies between passenger vehicles and commercial vehicles. These systems operate at pressures of 1,600 bar or higher. The common rail is a tube that supplies each computer-controlled injector containing a precision-machined nozzle and a plunger driven by a solenoid actuator **[23]** .

(C) Unit-injection system

Unit direct injection also injects fuel directly into the cylinder of the engine. In this system such in **Figure 2-4(C)** and **Figure 2-5**, the injector and the pump are combined into one unit positioned over each cylinder controlled by the camshaft.

Each cylinder has its own unit eliminating the high pressure fuel lines, achieving a more consistent injection. With recent advancements, the pump pressure has been raised to 2,400 bar.

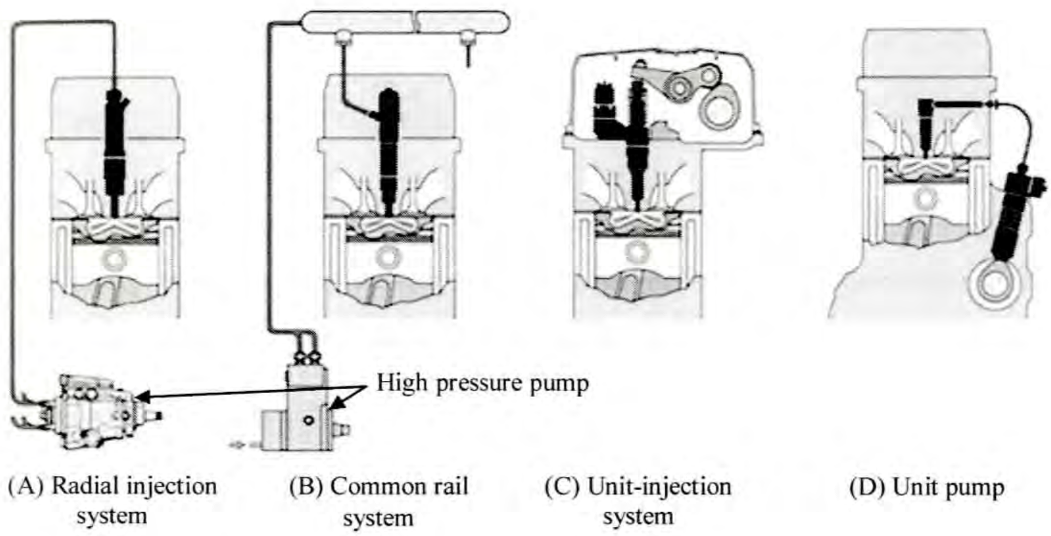

Figure 2-4 Types of Direct Injection System

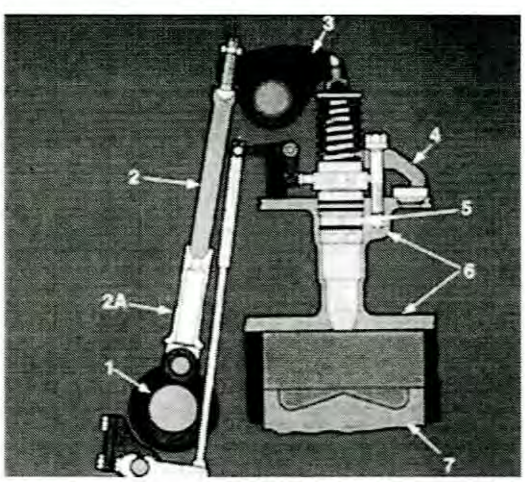

Figure 2-5 Unit Injection

As diesel engines evolved so did the fuel system. This is referred to as a pump, line and nozzle system. It is comprised of a fuel injector, high pressure line and fuel injection pump. The fuel pump is referred to as a bucket type fuel pump due to the type of cam follower in the pump. This basic design is still in use today such in **Figure 2-4(D)** and each system is optimized for a particular model engine.

The unit pump system is similar to the unit-injector system. This system is also placed directly in the engine cylinder block, but is operated by roller tappets on the engine's camshaft.

2.2.2 Main Components of Injection System

Main components of injection system are fuel tank, high pressure injection pump fuel filter and injection nozzle. The fuel tanks in diesel fuel systems usually are made of sheet metal or an aluminum alloy. The main function of this part is simply to hold the diesel or biodiesel.

The injection pump is responsible for delivering high-pressure fuel to the injector nozzle. In some engines, particularly small ones that have the fuel tank raised up above the engine, the injection pump is the only pumping mechanism used to deliver fuel from the tank to the injector. In most engines, a distribution or "lifter" pump first draws the fuel from the tank to the injection pump.

Traditionally, the pump is driven indirectly from the crankshaft by gears, chains or a toothed belt (often the timing belt) that also drives the camshaft on overhead-cam engines (OHC). It rotates at half crankshaft speed in a conventional four-stroke engine. Its timing is such that the fuel is injected only very slightly before top dead centre of that cylinder's compression stroke. In some system injection pressures can be as high as 200Mpa. There are three types of injection pumps are jerk or single-cylinder pump, inline pump and rotary pump.

Jerk pumps that showed in **Figure 2-6** are the simplest type of injection pump and are found only in single-cylinder engines. They use a piston-and-barrel-style mechanism to deliver fuel to the injector via a high-pressure pipe. The piston inside a jerk pump uses a timing mechanism running from the engine camshaft **[24]**.