International Journal of Mechanical Engineering and Robotics Research

ISSN 2278 – 0149 www.ijmerr.com
Vol. 2, No. 4, October 2013

Review Article

SCUDERI SPLIT CYCLE ENGINE: A REVIEW

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Internal Combustion engines have become a very important prime movers in today's life, there study is also an active field of research for many automobile industries and also has its environmental concerns. IC engines are used not only in automobile industries but are also used in transportation in sea as well as air, as a prime mover for electric generators and in industrial applications. There efficiencies and there environmental impacts are very crucial. A new IC engine developed by the Scuderi group called 'Scuderi Split Cycle Engine' is described in this review paper. It is more efficient than a conventional engine and also have less emissions.

Keywords: Conventional engine, Efficiency, Split cycle

INTRODUCTION

Scuderi Split-cycle engines divides the four strokes of intake, compression, power, and exhaust into two separate but paired cylinders. The first cylinder is used for intake and compression. The compressed air is then transferred through a crossover passage from the compression cylinder into the expansion cylinder, where combustion and exhaust occur. A Scuderi split-cycle engine is like an air compressor on one side with a combustion chamber on the other. The Backus Water Motor Company of Newark, New Jersey produced an early example of a split cycle engine as far back as 1891. From that time onwards various designs came out from different groups all over the world. Various engineers and scientists worked on it to explore the possibility of the split cycle engine. But, none has matched the efforts and the results obtained by Late Carmelo J. Scuderi. He gave his entire life for the Scuderi split cycle engine. The Scuderi Group, an engineering and licensing company based in West Springfield, Massachusetts and founded by Carmelo Scuderi's children, completed the prototype and unveiled it to the public on April 20, 2009.

PARTS OF THE SPLIT CYCLE ENGINE

1. Compression Cylinder

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2. Expansion Cylinder
3. Compression Piston
4. Expansion Piston
5. Crossover Passage and Crossover Valve
6. Intake/Exhaust Valve
7. Crank and Crankshaft
8. Fuel Injector
9. Spark Plug

Figure 1: Split Cycle Engine

Compression and Expansion Cylinder

The split-cycle engine design divides the four strokes of the Otto cycle between two cylinders—one suction/compression cylinder and another expansion/exhaust cylinder. The processes of suction and compression take place in the compression cylinder, and the processes of expansion and exhaust take place in the power cylinder. The compression cylinder consists of the a piston, inlet valve and the crossover compression valve whereas a power cylinder consists of a piston, exhaust valve, crossover expansion valve and the spark plug.

The efficiency of an internal combustion engine is increased if the gas is expanded more during the expansion stroke than it is compressed during the compression stroke. In Split Cycle Engine the design of compression cylinder is different from that of the expansion cylinder. The displacement volume of compression cylinder is less than that of the displacement volume of the power cylinder. This makes the expansion stroke greater than that of the compression stroke. Due to this arrangement more work is obtained in power stroke and less work has to be given in compression cylinder which is not possible in conventional IC engine.

Compression Piston and Expansion Piston

A compressor cylinder including a compression piston moves within the compression cylinder and it is connected to the crankshaft. Compression piston reciprocates through the suction stroke and the compression stroke during a single rotation of the crankshaft.

An expander cylinder includes an expansion piston which moves within an expansion cylinder and is connected to the crankshaft such that the expansion piston reciprocates through an expansion stroke and an exhaust stroke during a single rotation of the crankshaft.

Crossover Passage

A crossover passage interconnecting the compression and expansion cylinders, the crossover passage including a crossover compression (XovrC) valve and a crossover expansion (XovrE) valve. It also consists of a fuel injector. The crossover passage transfers the compressed air from the compression cylinder to the expansion cylinder and maintains the pressure in between the two cylinders. It consists of a fuel injector which injects the fuel in the passage.

Crossover Valve

Due to very high compression ratios (e.g., 20:1, 30:1, upto 100:1), an outwardly opening (opening outward away from the cylinder and piston) crossover compression (XovrC) valve at the crossover passage inlet is used to control flow from the compression cylinder into the crossover passage. Due to very high expansion ratios (e.g., 20:1, 30:1, upto 120:1), an outwardly opening crossover expansion (XovrE) valve at the outlet of the crossover passage controls flow from the crossover passage into the expansion cylinder.

Intake/Exhaust Valves

These valves are inwardly opening, i.e., towards the piston. Intake valve controls the intake of air coming in the compression cylinder and exhaust valve rejects the exhaust gases from the power cylinder to the surrounding.

Fuel Injector

This is used to inject the fuel where it mixes with air and forms a good mixture of air and fuel which is very important for the proper combustion of the charge.

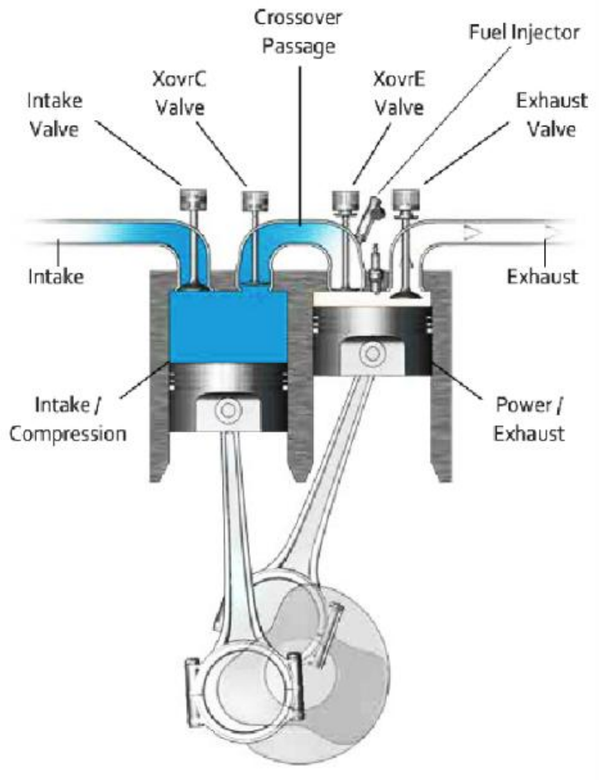
Crank and the Crankshaft

The pistons of both the compression and power cylinder are connected to the crank by crankshaft. When the crank rotates it drives the piston in the power as well as in the compression cylinder. Generally the expansion piston leads the compression piston by 20 degrees.

Spark Plug

It gives the spark necessary to ignite the fuel and start the process of combustion. It gives sufficient energy to the charge and raises the temperature of fuel to its ignition temperature.

Figure 2: Parts of Split Cycle Engine



WORKING OF ENGINE

The four strokes of the Otto cycle are "split" over the two cylinders such that the compression cylinder, together with its associated compression piston, perform the intake and compression strokes, and the expansion cylinder, together with its associated expansion piston, perform the expansion and exhaust strokes. The Otto cycle is therefore completed in these two cylinders once per crankshaft revolution (360 degrees CA) about crankshaft axis. The working of the engine is explained in four strokes:

1. Suction Stroke
2. Compression Stroke
3. Expansion Stroke
4. Exhaust Stroke

Suction Stroke

During the intake stroke, intake air is drawn into the compression cylinder through an intake manifold disposed in the cylinder head. An inwardly opening (opening inward into the cylinder and towards the piston) intake valve controls fluid communication between the intake manifold and the compression cylinder. The intake air is supercharged at 1.5 bar. A boosting device is connected to the intake manifold. The boosting device used is supercharger.

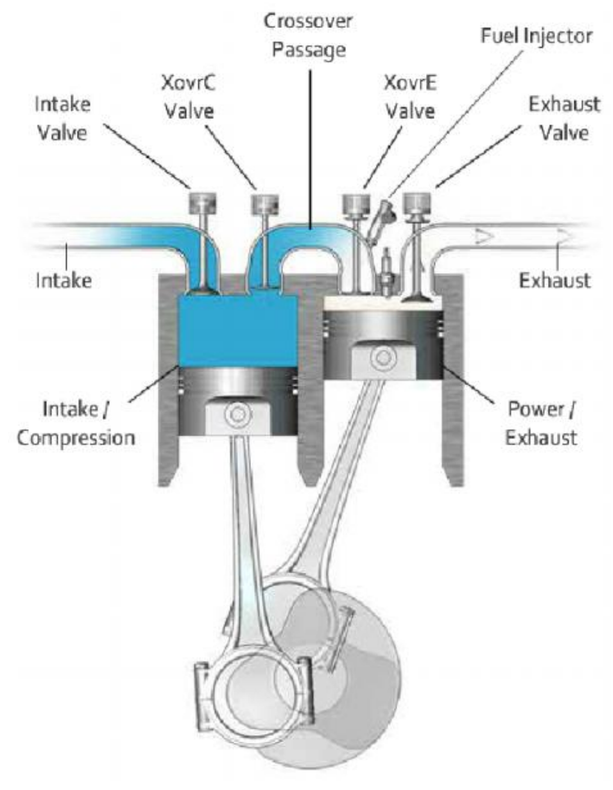
Compression Stroke

During the compression stroke, the compression piston pressurizes the air and, upon XovrC opening, drives the air to crossover passage. This means that the compression cylinder and compression piston are a source of high pressure gas to the crossover passage, which acts as the intake passage for the expansion cylinder. Fuel injector injects fuel into the pressurized air at the exit end of the crossover passage in correspondence with the XovrE valve opening, which occurs shortly before expansion piston reaches its top dead center position. At this time, the pressure in the crossover passage is more than the pressure in the expansion cylinder. Fuel is injected in the Cross over valve.

Expansion Stroke

When XovrE valve opens, the pressure in crossover passage is substantially higher than the pressure in expansion cylinder. This high pressure ratio causes initial flow of the air and/ or fuel charge to flow into expansion cylinder at high speeds. The air/ fuel charge usually enters the expansion cylinder shortly after expansion piston reaches its top dead center position (TDC), although it may begin entering slightly before TDC under some operating conditions.

Figure 3: Compression Stroke



As piston begins its descent from its top dead center position, and while the XovrE valve is still open, spark plug, which includes a spark plug tip which is fired to initiate combustion in that region. Combustion can be initiated while the expansion piston is between 1 and 30 degrees CA past its top dead center (TDC) position. More preferably, combustion can be initiated while the expansion piston is between 5 and 25 degrees CA past its Top Dead Center (TDC) position. The high speed flow of the air/fuel charge is particularly advantageous to split-cycle engine because it causes a rapid combustion event, which enables the split- cycle engine to maintain high combustion pressures even though ignition is initiated while the expansion piston is descending from its top dead center position. The XovrE valve is closed after combustion is

Figure 4: Expansion Stroke

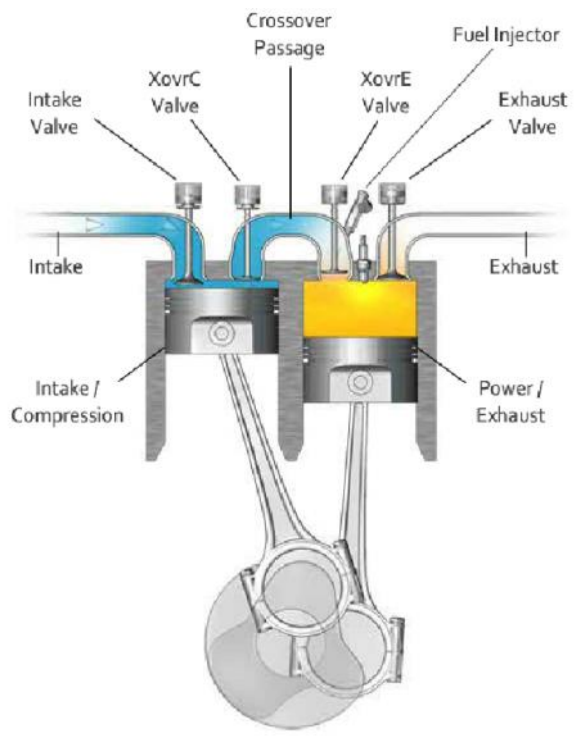
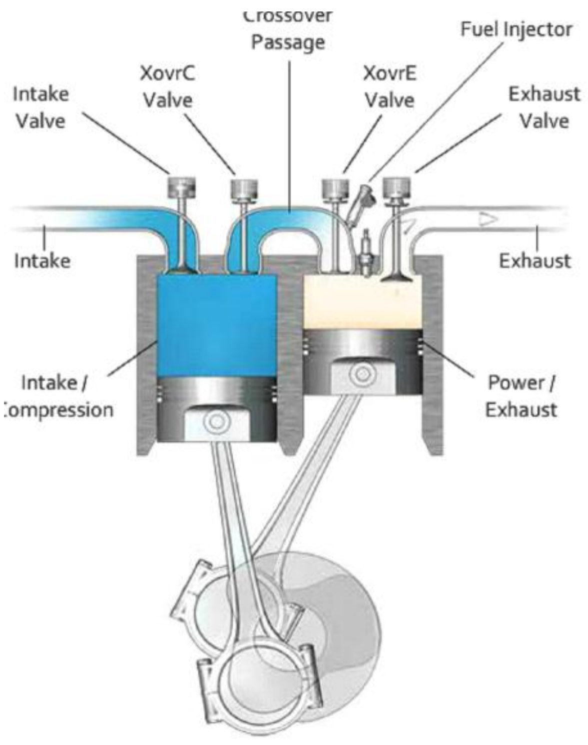


Figure 5: Exhaust Stroke



initiated but before the resulting combustion event can enter the crossover passage. The combustion event drives the expansion piston downward in the power stroke.

Exhaust Stroke

During the exhaust stroke, exhaust gases are pumped out of the expansion cylinder through exhaust valve disposed in cylinder head. An inwardly opening poppet exhaust valve, controls fluid communication between the expansion cylinder and the exhaust valve.

KEY FEATURES

After Top Dead Centre Firing (ATDC Firing)

Unlike conventional engine which are fired before top dead centre split cycle engine are fired after top dead centre, i.e., spark is generated when the pison starts its downward travel.

Reason for After Top Dead Centre Firing

In order to fire BTDC in a split-cycle engine, the compressed air, trapped in the crossover passage, is allowed to expand into the power cylinder as the power piston is in its upward stroke. By releasing the pressure of the compressed air, the work done on the air in the compression cylinder is lost. The power piston then recompresses the air in order to fire BTDC. By allowing the compressed gas in the transfer passage to expand into the power cylinder, the engine needs to perform the work of compression twice. In a conventional engine, the work of compression is done only once; consequently, it achieves much better thermal efficiency when split cycle engines are fired BTDC. Although considered bad practice in conventional engine design, firing ATDC in a split-cycle arrangement eliminates the losses created by recompressing the gas.

Benefits of After Top Dead Centre Firing

When the engine is fired before TDC, maximum combustion pressure is obtained at TDC. However at this position the connecting rod and the crankshaft throw are nearly aligned with the cylinder axis. Thus the pressure generated acts vertically downwards in line with the connecting rod. Whereas if engine is fired after TDC adjustments can be made to coincide maximum combustion pressure with maximum torque generated thus increasing the thermal efficiency.

Compression and Expansion Ratio

The volumetric (or geometric) compression ratio of the compression cylinder of split-cycle engine is herein referred to as the "compression ratio" of the split-cycle engine. The volumetric (or geometric) compression ratio of the expansion cylinder of split-cycle engine herein referred to as the "expansion ratio" of the split-cycle engine. The compression ratio of a cylinder is well known as the ratio of the enclosed (or trapped) volume in the cylinder when a piston reciprocating therein is at its Bottom Dead Center (BDC) position to the enclosed volume (i.e., clearance volume) in the cylinder when the piston is at its Top Dead Center (TDC) position. Specifically for split-cycle engines as defined herein, the volume of the crossover passage is not included in the determination of the compression ratio of a compression cylinder and the expansion ratio of the expansion cylinder.

Expansion Stroke

For every revolution of the crankshaft a expansion stroke is obtained unlike conventional engine in which a expansion stroke is obtained every 2 revolutions of the crankshaft.

AIR STANDARD CYCLE

The conventional SI engine works on the Otto cycle in the same way there should be an air-standard cycle for the split cycle engine. Two interesting points regarding the split engine cycle.

1. The split cycle has larger expansion ratio than the compression ratio: Unlike the conventional engine which has the same compression and expansion ratio the split cycle engine has more expansion ratio than the compression ratio.
2. Miller effect: The length of the power cylinder is more than the compression cylinder. In the conventional engine, the same piston executes the compression and power strokes, making it difficult for one stroke to be longer than the other. But Scuderi Split-Cycle Engine can accomplish this, enabling the engine to extract more energy from the burning fuel during the power stroke, by over expanding the gas.

Based on this two points the air standard cycle on which Scuderi Split Cycle is Miller cycle.

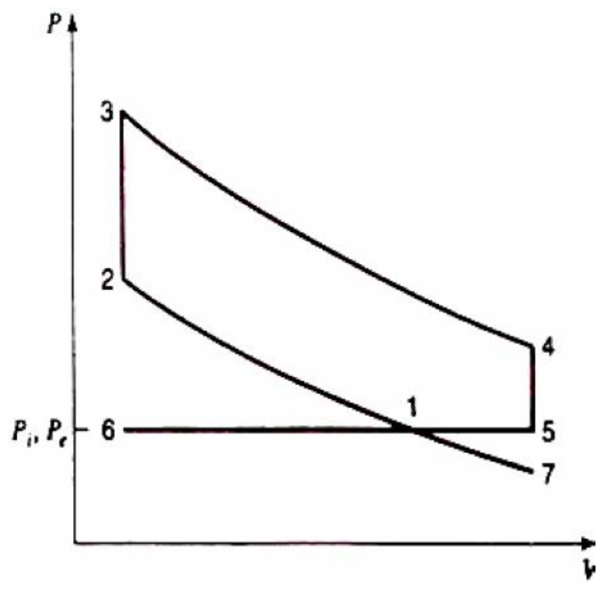
Miller Cycle

It is an over-expanded cycle, i.e., a cycle with an expansion ratio higher than its compression ratio. Apart from this it also fulfills the miller effect.

WORKING OF MILLER CYCLE

The efficiency of an internal combustion engine is increased if the gas is expanded more during

Figure 6: Miller Cycle



the expansion stroke than it is compressed during the compression stroke. In the Miller cycle, this is typically accomplished by:

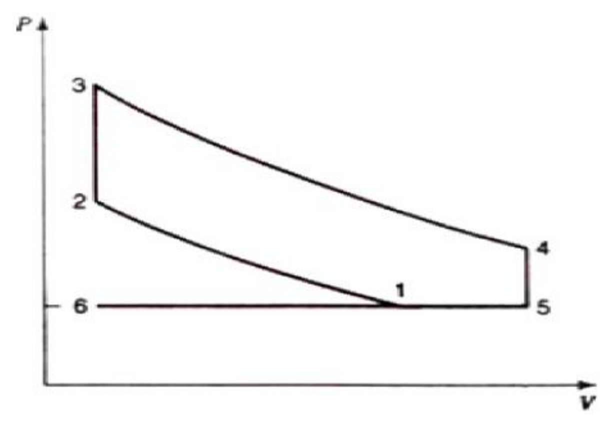
1. Early Inlet Valve Closing (IVC),
2. Late Inlet Valve Closing (IVC)

which decreases the effective compression ratio relative to the expansion ratio. For example, if the inlet valve of a conventional engine is closed late (i.e., during the compression stroke that follows the intake stroke), a portion of the intake air that was drawn into the cylinder during the intake stroke is pushed back out of the cylinder through the intake port. The intake valve may be kept open during about the first 20% to 30% of the compression stroke. Therefore, actual compression only occurs in about the last 80% to 90% of the compression stroke.

Miller Cycle Utilizing Late Inlet Valve Closing

Engine utilizing late IVC to effect Miller cycle operation is shown.

Figure 7: Late Inlet Valve Closing in Miller Cycle



From 6-5-1 and 5-1: During the intake stroke of the piston from TDC to BDC, the cylinder pressure follows a constant pressure line from point 6 through point 1 and finally to point 5.

During the initial portion of the subsequent compression stroke, while the intake valve is left open the cylinder pressure retraces the pressure line from point 5 back to point 1. Then, at point 1 the intake valve closes and the cylinder pressure increases from point 1 to point 2 during the remainder of the compression stroke. The volume swept by the piston along the path 1-5 is canceled by the volume swept along the path 5-1, and the effective compression ratio is the volume at point 1 divided by the volume at point 2 rather than the volume at point 5 divided by the volume at point 2 for the Otto cycle.

From 1-2: The compression piston pressurizes the air and, upon XovrC opening, drives the air into the crossover passage. The XovrC valve opens in between the compression stroke. Fuel injector injects fuel into the pressurized air at the exit end of the crossover passage in correspondence with the XovrE valve opening, which occurs shortly before expansion piston reaches its top dead center position. At this time the pressure in the crossover passage is more than that in the expansion cylinder.

From 2-3: The charge usually enters the expansion cylinder shortly after expansion piston reaches its Top Dead Center position (TDC), although it may begin entering slightly before TDC.

As piston begins its descent from its top dead center position, and while the XovrE valve is still open, spark plug, which includes a spark plug tip that protrudes into cylinder is fired to initiate combustion in the region around the spark plug tip.

From 3-4: The XovrE valve is closed after combustion is initiated but in such a way that products of combustion doesn't enter the crossover passage. The combustion event drives the expansion piston downward in the power stroke.

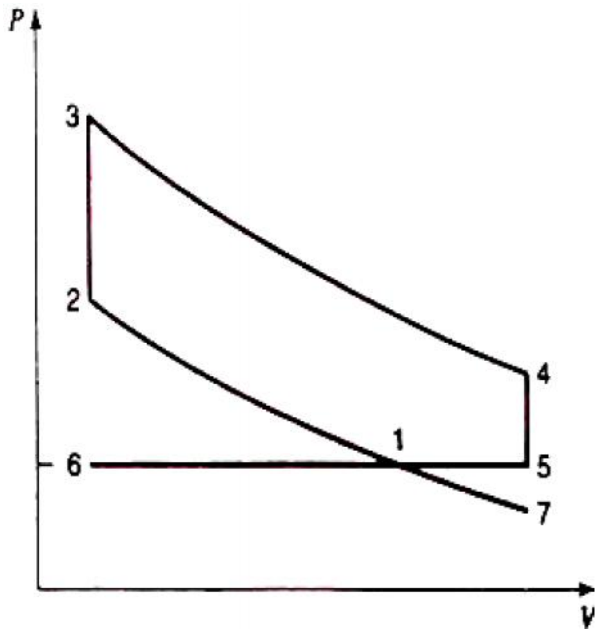
From 4-5: During this process the exhaust valve opens and the gases are released from the power cylinder when piston moves from its BDC to TDC.

Miller Cycle Utilizing Early Inlet Valve Closing

Referring to FIG, the same effect can be achieved in the Miller cycle by early inlet valve closing.

In this case, the pressure remains constant during the intake stroke from point 6 to point 1. Then at point 1 the intake valve closes, and the pressure in the cylinder decreases from point 1 to point 7. During the subsequent compression stroke, the pressure increases from point 7 to point 1, canceling the previously traced path, and continues to point 2 during the remainder of the compression stroke. The net result is the same as late intake valve closing. That is, less than the entire piston stroke is effectively used for compression, thereby decreasing the effective compression ratio.

Figure 8: Early Inlet Valve Closing in Split Cycle Engine



CONCLUSION

From the literature review it can be seen that this engine is more efficient than conventional engine due to its inherent features. The Scuderi Split Cycle Engine development is a result of the endeavour to increase the efficiency and reduce the emissions of the engine. The research in the development of this new engine is very unique attempt as compared to the researches going around world for two decades for improving the power output by installing additional accessories to the conventional engine. The research and development of Scuderi Split Cycle Engine is very essential because of high requirement of efficient engines with very less emissions are prevalent. It can be concluded that the Scuderi split cycle engines are more efficient than a conventional engine and therefore they are future alternatives of the conventional engines. Just like conventional engines which are used for power generation as well as in automobiles the split cycle engines could also be put to use in the similar situation.

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