Development of Combustion Cycle of HCCI Engine in a Two Stroke Reciprocating Gasoline SACI Engine

Iwan Harianton[1,3] and Iman K. Reksowardojo[2]
Noval Lilansa[3], Beny Bandanadjaja[3], Ayi Ruswandi[3], Suwadi Suparlan[3]
[1]Graduate Student and [2]Faculty of Mechanical and Aerospace Engineering (FTMD)
[3]IC Engine Research Team of Ministry of Research, Technology, and Higher Education
Bandung Institute of Technology
Jalan Ganesha 10, Bandung, Indonesia
Email: iwan_harianton@yahoo.com

Abstract

Homogeneous Charge Compression Ignition (HCCI) engine has been introduced a few decades ago by many researchers with several advantages to offer compared to the existing commercialized diesel or gasoline engines. The HCCI engines are commonly developed in four-stroke reciprocating engine both Spark Ignition or Compression Ignition engines. The main advantages of the HCCI engine are regardless of the fuel type, such machine offer higher thermal efficiency, low pollutants, and claimed to consume less fuel due to tight control of air fuel mixture. HCCI engine generates its power through compression ignition where the fuel is brought to its auto ignition condition.

The research idea is to develop combustion cycle of HCCI engine for two stroke reciprocating gasoline engine that can take fuel with RON number 90 or above such as Ethanol. However, it is expected to have higher ignition temperatures and higher compression ratio to make auto ignition condition fulfilled, which is not favorable to the engine design. Therefore, this research will introduce Spark Assisted Compression Ignition (SACI) to make auto ignition take place at lower temperature and lower pressure. The synthesis is that when portion of the fuel meet with abundant reserve of oxygen stimulated by spark will form kernel growth that make easier for the fuel to be burned. So that when the requirement for the air-fuel mixture established while kernel growth already started in milliseconds before TDC, the compression ignition can take place at the temperature below its auto ignition temperature. This phenomenon will be the basic research principle of developing combustion cycle of the two stroke SACI engine.

The combustion cycle development of two stroke SACI engine that is being researched involve several variables to be managed including fuel supply timing, present of oxygen in the combustion chamber, delivering spark before TDC, and the actual fuel auto ignition. The research only observe combustion chamber from 135 degrees BTDC and 5 degrees ATDC where compression ignition occurs from preparing to exploding. This paper will explain the design of combustion cycle and the research finding around this topic so that this research's contribution can easily be uncovered.

Key words: HCCI, 2-Stroke engine, combustion cycle of SACI engine, kernel growth, fuel injection timing, auto ignition.

INTRODUCTION

In the last two decades, human and good's mobility are increasing and it is expected to increase further in the coming years as the globalization agenda prevail. Massachusetts Institute of Technology Laboratory for Energy and Environment predicted that the use of fluid fuel will still dominate in the north America until 2035 [1], as it is in the European continent [2]. Even though such prediction will develop positive impact to the World's economy, it contributes significant harm to environment in the form of Green House Gas (GHG) emission, which contain Nitrogen oxides (NOx), Carbon monoxide (CO), Hydrocarbons (HC) and Particulate Matters (PM). Therefore, the world has agreed to fight on GHG emission reduction from vehicles along with the development of economic agenda worldwide.

One of the concrete proposal to overcome GHG emission problems given by an independent international consultant firm *Price Waterhouse Cooper, Automotive Institute* year 2007 that three possible actions where everyone may contribute through, including *Better Engine Concept*, *Beyond Engine Technology* and *Alternative Fuels* [3].

Spark Ignition (SI) Engine and Compression Ignition (CI) Engine are the two most common engine concepts available commercially; they are already utilized for more than one century after the significant invention of August Otto and Rudolf Diesel, respectively. The last three decades the two engine concepts have been advanced by numerous engine technology innovations including precision fuel injectors, electronic control unit, sensors, power spark plug, heat transfer arrangement, better effective cooling and lubrication, 3-ways catalytic converter, exhaust gas recovery, particulate traps, and lighter-tougher engine materials. CI Engine seems to lead the market of the 21st century because it offers higher thermal efficiency and becoming leaner due to advancement of control unit for air-fuel ratio throughout the combustion cycle, see figure 1 [2]. Meanwhile, SI engines even though still win in the passenger's car competition due to lighter engine design and lower pollutants, they convert energy on lower thermal efficiency level.

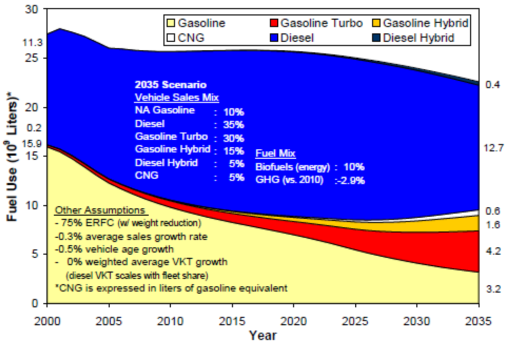


Figure 1. Petroleum fuels use in France

This research is entering the first stage of developing new engine concept carrying problems of SI Engine of being lower thermal efficiency and also carrying problems of two-stroke engine that almost left out by industry due to higher pollutants and consume more fuel for the same kilowatt hours of that generated by four-stroke engine. The research drive is because the two-stroke engine generates double power [4] and simpler engine design, which has potential for shorter production lead time and lower cost.

This paper will not discuss other two possible actions such that *Beyond Engine Technology* and *Alternative Fuels*, which are saved for further series of research advancement because they are equally important and significant.

METHOD AND MATERIALS

The research methods and materials are carefully selected to overcome each and every possible cause of research problems, which happen to include **reconstruction of the two-stroke** combustion chamber, **reconfiguration of Homogeneous Charge Compression Ignition** (HCCI) for gasoline type of fuel by utilizing Spark Assisted Compression Ignition (SACI), and **Combining tougher-lighter materials** for higher safety risk management in the alpha version.

Reconstruction of the 2-stroke Engine

As we are all aware that the two-stroke engine generates power in every rotation, while the four-stroke generates it in every two rotations. Therefore, the two-stroke engine has shorter time to complete its combustion cycle and so the reaction time between HC and O_2 is shorter too. Then, the analysis to assure proper air-fuel mixture is critical to prepare good combustion and eliminate particulate matters from incomplete combustion.

The two-stroke engine is definitely simpler compared to the four stroke engine, see figure 2 [5].

However, it has at least four weaknesses including **lower compression ratio** (CR), **inlet and outlet valve overlap**, **uncontrollable air-fuel mixture**, and **lower reliability to heat** resistance for rotating and moving components. Most recent two-stroke engine design has been improved significantly especially in the fuel consumption through injection nozzle and inlet and outlet valve overlap. But those two-stroke engines are applied for big size engines to run in lower speed so that the time to let HC and O_2 in reaction will be still possible. It is not yet the case in smaller size engines.

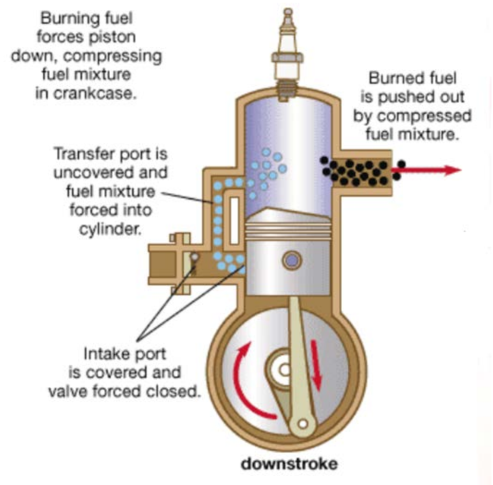


Figure 2. Two-stroke engine Basic design

Thermal efficiency is higher when the **CR** is high and property of working gas γ is high too, see formula 1 [6].

$$\eta_{th} = 1 - (1/CR^{\gamma-1}) \quad (1)$$

Where: η_{th} = Thermal efficiency
CR= Compression Ratio
γ = Cp/Cv

Reconfiguration will need to allow higher CR meaning that inlet and outlet valve overlap should happen in the lowest level possible to gain higher compression ratio. Inlet and outlet valve overlap should not involve fuel supply to eliminate possible waste of fuel in the combustion cycle.

Other concern is **about air-fuel ratio,** λ (read lambda); where old design of two-stroke engine has little control over such issue. Today, air-fuel ratio or λ has been the main concern of researchers to make combustion more effective. The issue is about the control of O_2 supply extracted from the ambient air, which happens to consist of about 21% of O_2 and 71.9% Nitrogen and others gas form substances [6]. Such control has been made possible technologically under λ sensor installed in the exhaust manifold to deliver feedback through the electronic control unit that manage air supply based on the throttle demand.

Reconfiguration HCCI to SACI

To improve the thermal efficiency and emission of SI Engine, researchers had proposed a new combustion concept, Homogeneous Charge Compression Ignition (HCCI). Lund university research center headed by professor Bengt Johansson has been conducting the research since two decade ago suggested that HCCI has potential to improve thermal efficiency, even though it has great challenge in a high load engine [7]. His work actually followed by other researchers too. Publication of HCCI concept first appeared in the International Journal for Society of Automotive Engineering in 1983 by Najt P., and Foster D. E. [8] for four-stroke engine aims to improve both increasing thermal efficiency and decreasing emissions, Thring R. H. in 1989 again published HCCI with the goal to improve thermal efficiency, lowering fuel consumption and decreasing emissions by tight control of air-fuel ratio [9]. From the last two decades up to now, other names are also used to describe similar type of combustion, such as Compression Ignited Homogeneous Charge (CIHC), Premixed Charge Compression Ignition (PCCI), Controlled Auto Ignition (CAI) combustion, Active Thermo-Atmosphere Combustion (ATAC), which are used for more specific type of HCCI combustions.

Olof Erlandsson published his research on the re-development of Early Swedish Hot-Bulb Engines – Efficiency and Performance Compared to Contemporary Gasoline and Diesel Engine [10]. It was the two-stroke engine used for rural application and agro vehicles was surprisingly better performance compared to the gasoline and diesel engine available commercially. Instead of tracking back to the past advancement, this research introduce new approach influenced by already available control unit and engineering components such as injectors, electronic control unit and sensors. Table 1 illustrates important parameters of selected fuel to be managed.

Table 1. Properties of fuels

	Density	Boiling point	Specific heat	Ignition temp
Liquid fuleds	kg/m^3 [a]	^{o}C	MJ/kg	^{o}C
Methanol	790	65	19.7	455
Ethanol	790	78	26.8	425
Gasoline	720-775	25-210	43.5	~ 400
Diesel	820-845	110-400	42.5	> 200
Vegetable Oil	900-930	220-320	36	…
Biodiesel RME	860-900	330-350	36	~ 150
Gaseos Fuels	kg/m^3 [b]			
CNG	0.7-0.84	> - 162	~ 32-45	~550
LPG	2.25	> - 42	46.1	~ 400
DME	0.67	- 20	27.6	~ 200
[a] at 15^{o}C [b] at 1.013 mbar				

From table 1, Gasoline auto ignition temperature is around 400 ^{o}C or twice as it is for the Diesel fuel. Therefore, it will need higher pressure to get such hot situation. While higher pressure will need tougher material or thicker wall for the same material. Reuss D. L. et.al develop low pressure compression ignition assisted by spark to build early Kernel growth before combustion ignition take place [11]. His formation for combustion cycle is presented in figure 3.

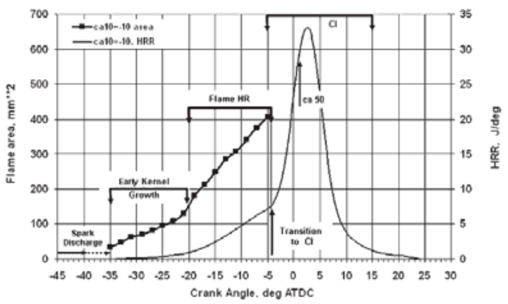


Figure 3. SACI Combustion cycle

The idea was to establish early HC and O_2 reaction as early as possible, which is in favor to the development of SACI in two-stroke engine. However, the original idea of this research was to deliver spark discharge at 5^o ATDC will continue to be implemented along with Reuss idea, especially in the cold start.

Material Selection

The material selection will have several possibilities depend on the function and environment. Constructing the engine should definitely follow the rule and regulation.

Potential candidate by benchmarking to the existing engine, they are Cast Iron (FC) that is good to absorb vibration [12], Ductile Cast Iron (FCD) that is a good candidate for crankshaft due to its characteristic on high strength while it is high machinability material [12]. Aluminum allow is commonly used for piston because it is light, high strength, and can be treated for high temperature resistance [13]. St.60 is high strength steel treatable to meet surface hardening as it work to connect piston with its connecting road that work involving friction in high force transmission to crankshaft [14].

RESULTS AND DISCUSSION

To elaborate the first stage of the research result, here will be presented the **reconstruction of the two-stroke engine**, **reconfiguration of the HCCI combustion** to the 2-stroke SACI combustion, and **selection of materials** for the new heat load and pressure.

Reconstruction of the 2-stroke engine

Reconstruction started with the correction of the CR from below 6:1 to become 12:1 so that the potential higher thermal efficiency will be achieved, see figure 4. The reconstruction continue by identifying the temperature of the design using formula 2, by assuming ideal cycle (reversible and adiabatic) or isentropic cycle [4].

$$T_2 = T_1 * CR^{(\gamma-1)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (2)$$

Where: CR = 12

γ = 1.3

T_1 = 80 ^{o}C (30 ^{o}C at Cold Start)

So that the Ignition Temperature T_2 will be 349.2^{o}C at cold start and 431.4^{o}C at the working temperature, which are high enough to have auto ignition to take place even with high RON number above 90 of fuel.

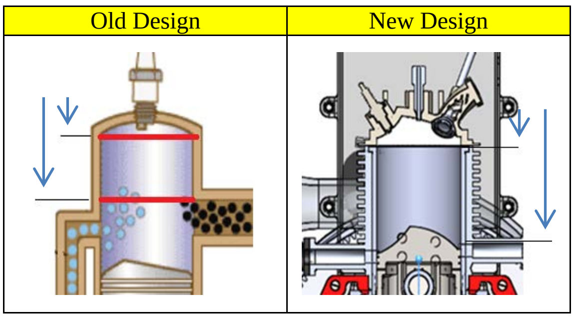


Figure 4. Reconstruction of higher CR

Reconstruction continue to eliminate inlet and outlet valve overlap, so that there will be no waste of fuel in the combustion cycle. Figure 5 has been done to do so.

International Journal of Scientific Engineering and Applied Science (IJSEAS) – Volume-2, Issue-4,April 2016
ISSN: 2395-3470
www.ijseas.com

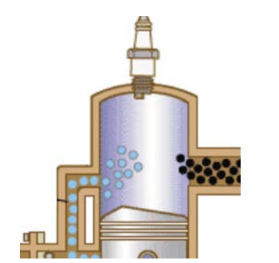
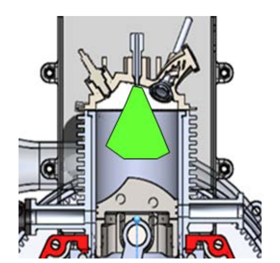
Old Design	New Design
	

Figure 5. Eliminate waste of fuel

The third construction was done to manage heat. By constructing blower directly connected to the crankshaft and deliver the air through special flexible hose to relieve excess heat and monitored through sensor to get feedback on the working temperature of 80^{o}C. Figure 6 illustrates the Computational Fluid Dynamic (CFD) capture on cleaning and cooling combustion chamber in every cycle.

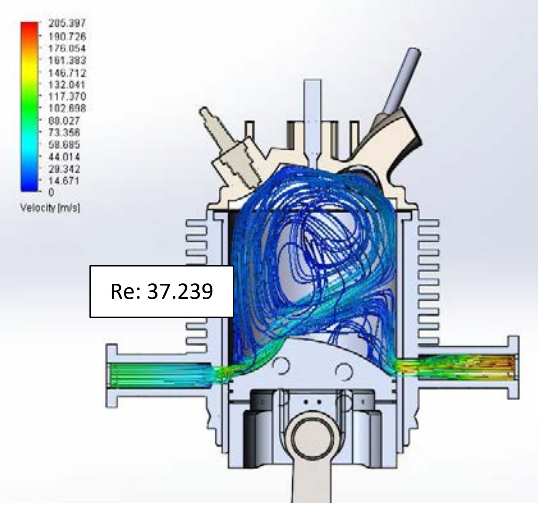


Figure 6. Cleaning and Cooling Chamber

Reconfiguration the combustion cycle

HCCI combustion is a compression ignition type of combustion, which has characteristic of multi auto ignition that take place in a wide spread of places in the combustion chamber.

While, Spark Ignition type, which has characteristic of single big concentrated localized type of combustion. HCCI deliver more power to the shaft due to less fuel energy dissipated to atmosphere [15].

The combustion cycle being develop starts from 135^o BTDC up to 5^o ATDC. The cooling and cleaning combustion chamber ends at 135^o BTDC where inlet and outlet manifolds are closed by the position of piston. Piston is continue to advance until it reaches 90^o BTDC where 70% of fuel injected and spark is discharged in early position to help air-fuel mixture to form Kernal growth composing HCs + O_2s, which are continue to grow by the swirling effect of the charge, before it closed at $\lambda>1$. At exactly 10^o BTDC 30% of fuel again injected to complete the throttle demand and λ will be around 1.0 – 1.1. Auto ignition began to form from 10^o BTDC until 5^o ATDC. Spark will then discharge at this point to finish up all available air-fuel mixture especially in the cold start. Spark will be off when the engine are already in the working temperature around 80^{o}C.

The main concern of the HCCI combustion is to control of the O_2 supply to the pumped HC on gas pedal throttle demand, while within the short period of time they should meet each other adequately. The design should be verified to achieve Reynold Number (Re) above 4.000 as it complies with equation 3 [16]. Re below 2.300 fluid flow in laminar flow, while Re between 2.300 – 4.000 it flows in "transition flow".

$$Re = D\, V\, \rho / \mu \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

Where: D = Tube Diameter
V = Average Velocity
ρ = Fluid density
μ = Fluid viscosity

Figure 7 illustrates the CFD simulation on the newly develop inlet air swirling manifold that has potential to create turbulence condition [17], [18].

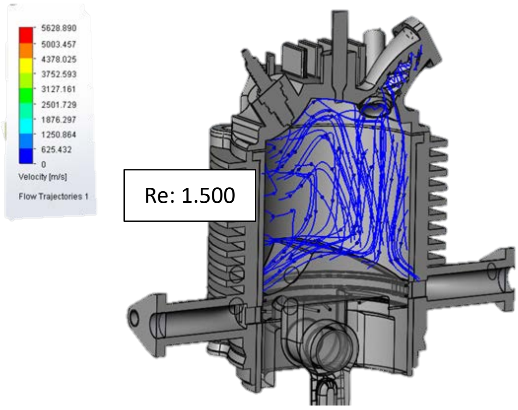


Figure 7. Swirling effect air-fuel mixture

The swirling manifold will not be discussed here as it saved for property right registration and saved for specific development in the effectiveness of the the air-fuel mixture.

Materials Selection

Table 2 illustrates the material selected to overcome different loadings and conditions of *alpha* version of the engine, which will then be reviewed for optimal performance in *beta* and *gamma* versions before entering production stage next year.

Table 2. Internal loading and situation

Components (Material)	Loadings
Cylinder head (FC 30)	Expose to heat cyclic loading from 140^{o}C to 550^{o}C.
Cylinder Liner (FC 30)	Expose to heat cyclic loading from 140^{o}C to 450^{o}C and to friction wear.
Upper Crankcase (Al Alloy 2025)	Heat exchange from liner to ambient, expose to heat of ~ 140^{o}C.
Piston (Al Alloy 4032)	Expose to heat from combustion, and transfer Force to connecting rod.
Piston pin (SNI St.45)	Connect piston to connecting road
Connecting rod (SNI St.60)	Transmit torque to crankshaft.

Components (Material)	Loadings
Lower Crankcase (FC 30)	Oil bath, holding Crankshaft, torque loading
Crankshaft (FCD 30)	Transmit torque to work

FC 30 is Ferro Casting or cast iron with high Carbon content between 3.2% to 3.7% form Perlite structure (worm) so that it will be very effective to absorb vibration in high temperature up to 760°C.

FCD 30 is Ferro Casting Ductile or ductile cast iron with carbon content from 3.5% to 3.8% but having structure of spherical graphite and surrounded by ferrite-perlite. Such structure offers higher strength, better machinability and heat treatable, which is suitable for high load crankshaft.

Al Alloy 2018, 2218, 2025, 4032 are those specific Aluminum Alloys treatable to meet heat resistance requirement as it is applied in the piston, IC Engine and heat related application.

St 60 is high strength steel treatable to surface hardening, it works to connect piston with its connecting road involving friction in high force transmission to crankshaft.

CONCLUSION

The combustion cycle development of two stroke SACI engine that is being researched has been designed to offer higher thermal efficiency, lower fuel consumption due to tight control of air-fuel mixture and no valve overlap, which all these development have been made possible through reconstruction of the 2-stroke engine with higher compression ratio, eliminating inlet–outlet overlap, managing several variables including fuel supply timing, present of oxygen in the combustion chamber, swirling motion of inlet charge, delivering spark BTDC, and maintaining the actual fuel auto ignition through close loop control system.

ACKNOWLEDGEMENT

This research has been made possible by continuing support from my promotor Dr. Iman K. R., and Professor Yatna Y. M., who are always there whenever I need for solution in the area of their expertise. I also feel very lucky to have trust and respect from my Rapid research team Dr. Noval Lilansa, Mr. Ayi Ruswandi, Dr. Beny Bandanajaya, and Mr. Supardi Suparlan who are encouraging me to develop IC Engine research topic as my dissertation. Also I would like to thank Mr. Marlin Siagian and Mr. Bambang who are willing to share their facility to do prototyping and build manufacturing production in their casting plant. All my colleagues in graduate classes who are very supportive to pursue scientific understanding and technology in FTMD-ITB.

REFFERENCES

[1]. Bandivandekar, A., et.al (2008), On the Road in 2035: Reducing Transportation's Petroleum Consumption and GHG Emissions, MIT Lab. for E&E. 77 Massachusetts Avenue, Cambridge, MA 02139 USA.

[2]. Kristian Bodek and John Heywood (2008), Europe's Evolving Passanger Vehicle Fleet: Fuel Use and GHG Emissions Scenarios Through 2035, MIT Lab. for E&E. 77 Massachusetts Avenue, Cambridge, MA 02139 USA.

[3]. .... (2007), Price Waterhouse Cooper, Automotive Institute.

[4]. Harianton, I., Ruswandi, I., and Nurdin, M., (2014), Design of New Ecological Combustion Engine With Double Potential Power Output, Applied Mechanics and Materials Vols 465-466 pp. 428-432.

[5]. www.encyclopediabritanica.com (2007), Encyclopedia Britanica, Incorporated.

[6]. Pischinger, R. and Klell, M. (2008), Jenbacher Energy Systems, TUG, Austria.

[7]. Johansson, B. (2011), Low temperature combustion requires high dilution level - A challenge at high load, Div. of Combustion Engine, Dept. of Energy Sciences - Lund University.

[8]. Najt P., and Foster D. E., (1983), Compression Ignited Homogeneous Charge. International Journal Society of Automotive Engineers paper number 830264

[9]. Thring, R. H. (1989), Homogeneous Charge Combustion Ignition. International Journal Society of Automotive Engineers paper number 892068.

[10]. Erlandsson, O., "Early Swedish Hot-Bulb Engines - Efficiency and Performance Compared to Contemporary Gasoline and Diesel Engines," SAE Technical Paper 2002-01-0115,2002,doi:10.4271 /2002-01-0115.

[11]. Reuss, D.L., Kuo, T.-W., Silvas, G., Natarajan, V., ans Sick, V., (2008), Experimental metrics for identifying origins of combustion variability during spark-assisted compression ignition, International Journal of Engine Research, Vol 9, pp. 409-434.

[12]. American Foundryman Society Handbook 2009.

[13]. MIL-HDBK 694A (1966), Military Standardized Handbook for Alluminum Alloy Handbook and its treatment.

[14]. ASM Handbook 1991 Vol 4. Heat Treating.

[15]. Najt, P., Kuo, T.-W., Cleary, D., Eng. J., and Brown, B., (2005), Auto-ignition gasoline engine combustion chamber and method, US Patent US 6,971,365 BI.

[16]. O. Reynolds (1883), An Experimental Investigation of the Circumstances which whether the motion of Water should be direct or sinuous or the law of Resistance in the Parallel Channels, Philosophical Transactions of the Royal Society of London 174, 935-982.

[17]. Persson, H., Johasson, B., Remon, A., (2007), The effect of swirl on Spark Assisted Compression Ignition (SACI), JSAE 20077167, pp. 365-375.

[18]. Harianton, I., et. al. (2015). Development of Two Stroke Double Power Ecological Engine with Spark Assisted Compression Ignition in Lean Mixture. International Journal of Energy and Power Engineering; 4(2) 118-22.