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Experimental and Computational of Engine Cylinder Pressure Investigation on the Port Injection Dedicated CNG Engine Development

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Abstract: This study has been investigated the effect of diesel engine convert to sequential port injection dedicated CNG engine on the engine cylinder pressure performance. This research has using GT-Power computational engine model for steady-state and transient simulation and experimental investigation. The investigation and simulation of the engine cylinder pressure performance characteristic profile based on variation engine speed. The engine computational model and experimental has developed based from the diesel engine converted to port injection dedicated Compressed Natural Gas (CNG) engine spark ignition. The simulation and experimental results of cylinder pressure characteristics are shown the cylinder pressure profile and maximum cylinder pressure characteristics. The results shown that the conversion development has decreasing the engine cylinder pressure.

Key words: CNG engine, engine cylinder pressure, engine speed, GT-Power computational model, port injection

INTRODUCTION

Gasoline and diesel fuel will become scarce and most costly (Catania *et al*., 2004; Hollnagel *et al*., 1999). Alternative fuel technology, availability and use will become more common in the coming decades for internal combustion engines. Nowadays, the alternative fuel has been growing due to concerns that the reserves of fossil fuel all over the world are finite and at the early decades of this century will run out completely. Furthermore, the current world energy crisis made the fossil fuel price increases. In the other hand, the fossil fuel contributes large environment pollution. Many types of alternatives fuels available in the world. Compressed Natural Gas (CNG) as an alternative fuel is becoming increasingly important.

This study is conducted to studies the computational and experimental of cylinder pressure performance in the development of diesel engine convert to port injection dedicated Compressed Natural Gas (CNG) engine. The baseline engine is a single cylinder four stroke direct injection diesel engine. The computational simulation is using GT-Power software. The experimental investigation of the baseline diesel engine and port injection dedicated CNG engine are using eddy current dynamometer. The objective of this research is to investigate the correlation of characteristic pressure performance in-cylinder of port injection CNG engine model based on engine speeds variation. The results output of port injection CNG engine is compared with base direct injection diesel engine model in-cylinder pressure performance.

The computational model of diesel engine covert to port injection CNG engine has been developed in the research. In the first step, is investigated the CNG engine intake port steady-state and transient of gas flow temperature simulation using GT-Power. This research is the second step and focuses in-cylinder pressure performance of single cylinder four stroke port injection CNG engine converted from direct injection diesel engine. The aim is to give an insight into the CNG engine in-cylinder gas of low thermodynamics performance using GT-POWER simulation model, how the engine model developed and the components interact. To determine port injection CNG engine pressure performance in-cylinder the engine is the essence of modeling at small intervals of time. Appropriate summation of these gas conditions over an engine cycle then leads to an estimate in-cylinder engine pressure performance.

In the port injection CNG engine, fuel is injected by the gas fuel injection system via intake port trans valve into the engine cylinder toward the end of the compression stroke, just before the desired start of

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combustion. The gas fuel, usually injected at high velocity as one or more jets through small orifices or nozzles in injector tip. The gas fuel mixes with high temperature and high pressure in-cylinder air. Since, the air temperature and pressure are in the gas fuel's ignition point, spark ignition of portions of the already-mixed fuel and after air a delay period of a few crank angle degrees. The cylinder pressure increases as combustion of the gas fuel-air mixture occurs. The major problem in port injection CNG engine combustion chamber design is achieving sufficiently rapid mixing between the injected gas fuel and the air in the cylinder to complete combustion in the appropriate crank angle interval close to top-center (Blair, 1999; Challen and Baranescu, 2003; Heywood, 1998; Kowalewicz, 1984; Richard, 1997).

Cylinder pressure changes with crank angle as a result of cylinder volume change, combustion, heat transfer to chamber walls, flow into and out of crevice regions and leakage. The effect of volume change on the pressure can readily be accounted for combustion rate information from accurate pressure data provided of model. Cylinder pressure versus crank angle data over the compression and expansion strokes of the engine operating cycle can be used to obtain quantitative information on the progress of combustion. Suitable methods of analysis which yield the rate of release of the fuel's chemical energy, or rate of the burning will be described in the study. Any researcher have been studied in-cylinder pressure and temperature in some bases of engine operation. Piedrahita *et al.* (2003) has studied the engine cylinder pressure and temperature under different operation parameters, such as air-fuel ration and spark angle advance, a zero-dimensional model is applied. Eriksson and Andersson (2002) has studied an analytic model for cylinder pressure in a four-stroke SI engine, the study describe the in-cylinder pressure of a spark ignited combustion engine operating close to stoichiometric conditions, as a function of crank angle, manifold pressure, manifold temperature and spark timing. Sanders *et al.* (2003) has studied of gas temperature measurements during ignition in an HCCI engine. The measurements results were made during the compression and early portion of the combustion phase of an n-heptane-fueled HCCI engine. The measured pressure-temperature history was compared to kinetic calculations of the ignition delay and showed the traversal of the negative temperature coefficient regime. In-cylinder combustion pressure characteristics of Fischer-Tropsch and conventional diesel fuels in a heavy-duty compression ignition engine. Christopher *et al.* (1999) has studied the in-cylinder combustion pressure traces obtained during the engine testing were analyzed to obtain several pressure-based variables including ignition delay, combustion duration, peak pressure, location of peak pressure, relative quantities of premix and diffusive burn heat release, indicated mean effective pressure and location of one-half of the mass fraction burned. Klein and Eriksson (2002) has studied compression estimation from simulated and measured cylinder pressure.

Most of cylinder pressure investigation is usually measured with piezoelectric pressure transducers. In this study, the cylinder profile is investigated using computational simulation software from the real compression ignition engine data then convert to port injection CNG engine spark ignition. The software have used in the research is GT-POWER software. The GT-POWER is the leading engine simulation tool used by engine and vehicle makers and supplies and is suitable for analysis of a wide range of engine issues. GT-POWER is designed for steady-state and transient simulation and can be used for analysis of engine and power train control (Semin *et al.*, 2008). It is applicable to all types of internal combustion engines and provides the user with many components to model any advanced concept. The GT-POWER is based on one dimensional gas dynamics, representing the flow and heat transfer in the piping and in the other components of an engine system. In addition to the flow and heat transfer capabilities, the code contains many other specialized models required for system analysis. The GT-POWER has the capability to model all of the aspects of the engine in the schematic and more. By being comprehensive, the code is well suited for integration of all aspects arising in engine and vehicle development. GT-POWER can be used for a wide range of activities relating to application and prediction of engine design and development. A user friendly interactive post processing tool, GT-Post, can be used to manipulate and view all of the plot data generated by cases RLT. Important performance data can be plotted against parameters from a multiple case run (Semin *et al.*, 2009).

The idealized P-V diagram used to determine the cylinder pressure (Heywood, 1998). The area of this curve must match the specified indicated output at the engine operating condition. The transition point in the figure marks the transition between the combustion and expansion segments of the power stroke. It can set the slope of the combustion segment with the slope of P-V curve after TDC attribute and GT-POWER will adjust the transition point so that both the indicated output and the slope are satisfied. The slope is defined by Eq. 1 and 2.

$$P = P_{max}\left(\frac{V_{TDC}}{V}\right)^{m} \quad (1)$$

$$P_{max} = P_{IVC} R_c^{\gamma} + P_{comb} \quad (2)$$

where, P is instantaneous cylinder pressure between TDC and transition point, P_{max} is maximum cylinder pressure or pressure at TDC, V_{TDC} is cylinder volume at TDC, V is instantaneous cylinder volume between TDC and the transition point, m is slope of P-V curve after TDC, P_{IVC} is cylinder pressure at IVC, R_c is cylinder compression ratio, γ is specific heat ratio and P_{comb} is pressure rise due to combustion.

If P is instantaneous cylinder pressure (bar) and V_{disp} is displacement volume (m^3), cylinder indicated mean effective pressure (imepc) of internal combustion engine is formulated in Eq. 3.

$$imepc = \frac{\oint PdV}{V_{disp}} \quad (3)$$

If P is instantaneous cylinder pressure (bar) and V_{disp} is displacement volume (m^3), pumping mean effective pressure (pmepc) in-cylinder of internal combustion engine is formulated in Eq. 4.

$$pmep = \frac{\int_{180}^{-180} PdV}{V_{disp}} \quad (4)$$

MATERIALS AND METHODS

The conversion development of four stroke direct injection diesel engine to sequential port injection dedicated Compressed Natural Gas (CNG) engine spark ignition are conducted on 2006-2008 at Automotive Laboratory, Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia.

The new design and development in this engine research activities are direct injection diesel fuel system changed to port injection CNG system, reduce compression ratio, compression ignition converted to spark ignition, mechanical fuel control changed to electronic fuel control system. In the CNG injection fueling system, the port injection of compressed natural gas fuel injector nozzle is used and then using new injector nozzle multi holes geometries. The basic fueling system management of four stroke direct injection diesel engine is using mechanical fueling pump system and fuel injected directly to the engine cylinder. The fueling system management of the engine will be changed to electronic control fueling system management for CNG fueling system and gas fuel is injected sequentially via intake port before intake valve.

Computational method: Port injection dedicated Compressed Natural Gas (CNG) spark ignition engine computational model is developed using GT-POWER software based from real diesel engine data. According to Semin *et al.* (2008, 2009) the specification of engine is shown in Table 1. In the GT-POWER engine model development, a typical engine cylinder is modeled using EngCylinder name and shown using number 11, engine is modeled using EngineCrankTrain component objects and shown using number 12, Valve*Conn and EngCylConn are connection objects. Engine parameters are shown in Table 1.

In the diesel engine and port injection CNG engine model development using GT-POWER, a typical engine is modeled using EngCylinder and EngineCrankTrain component objects and Valve*Conn and EngCylConn connection objects. EngCylinder and EngineCranktrain are used to define the basic geometry and characteristics of engine. Both objects further refer to several reference objects for more detailed modeling information on such attributes as combustion and heat transfer. Cylinder must be connected to the engine with EngCylConn part made from the predefined object which available in the template library. While EngCylConn parts have no user defined attributes, the global cylinder number for cylinder is assigned by the port number where the EngCylConn connection is attached to the engine. Cylinder are connected to intake and exhaust ports with Valve*Conn connections. Many Valve*Conn connection templates are available to define different types of valve and their characteristics.

To develop of single-cylinder four-stroke direct-injection compression ignition engine model and port injection CNG engine model using GT-POWER software is step by step, the first step is open all of the selected diesel engine components to measure the engine components part size. To create the GT-POWER model, select window and then tile with template library from the menu. This will place the GT-POWER template library on the left hand side of the screen. The template library contains all of the available templates that can be used

Table 1: Specification the engine

Engine parameters	Diesel engine	CNG engine
Bore (mm)	86.0	86.0
Stroke (mm)	70.0	70.0
Displacement (cc)	406.0	406.0
Compression ratio	20.28	14.5
Intake valve close (CA)	496	496
Exhaust valve open (CA)	191	191
Intake valve open (CA)	361	361
Exhaust valve close (CA)	325	325
Ignition system	Compression	Spark
Fuel intake system	Direct injection	Sequential inject
Fuel	Diesel	CNG

in GT-POWER. Some of these templates those that will be needed in the project need to be copied into the project before they can be used to create objects and parts. For the purpose of this model, click on the icons listed and drag them from the template library into the project library. Some of these are templates and some are objects that have already been defined and included in the GT-POWER template library. Then, the engine components size data input to the GT-POWER library of the all engine components data. All of the parameters in the model will be listed automatically in the case setup and each one must be defined for first case of the simulation. According, Abu Bakar (2007), the diesel engine model is shown in Fig. 1. The conversion of diesel engine model data to spark ignition port injection CNG engine is shown in Fig. 2.

In the port injection dedicated Compressed Natural Gas (CNG) spark ignition engine model is added intake pipe and throttle, then fuel is injected using injector in intake manifold. The engine computational model using GT-Power software is shown in Fig. 2. A typical intake manifold is modeled using 9, engine cylinder is modeled using 11 and engine is modeled using 12, then Valve*Conn and EngCylConn connection objects. Nine is used to define the basic geometry and characteristics of intake manifold, 11 and 12 are used to define the basic geometry and characteristics of engine cylinder and engine crank train. These objects further refer to several reference objects for more detailed modeling information on such attributes as gas flow temperature. Intake manifold must be connected to the engine cylinder with Valve*Conn, Engine cylinder must be connected to the engine with EngCylConn part made from the predefined object which available in the template library. While Pipe, EngCylConn parts have no user defined attributes, the global cylinder number for cylinder is assigned by the port number where the EngCylConn connection is attached to the engine. Cylinder are connected to intake and exhaust ports with Valve*Conn connections. Many Valve*Conn connection templates are available to define different types of valve, port and their characteristics. In this research, the simulation results of GT-Power engine computational model performance are focused on engine cylinder pressure. The simulation results are shown in plotting and report tables in GT-Post, graphical RLT viewer and order analysis of flow data. The solver of GT-POWER determines the main performance of an engine simulation based on engine speed mode in the EngineCrankTrain object in this research. Speed mode is the most commonly used mode of engine simulation, especially for steady states cases. In the research imposes the engine speed as either constant or by a dependency reference object. This method typically provides steady-state results very quickly because the speed of the engine is imposed from the start of the simulation, thus eliminating the relatively long

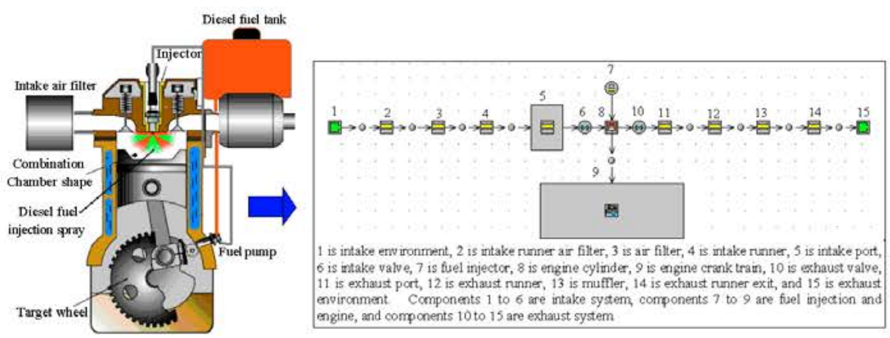

Fig. 1: Diesel engine model using GT-POWER

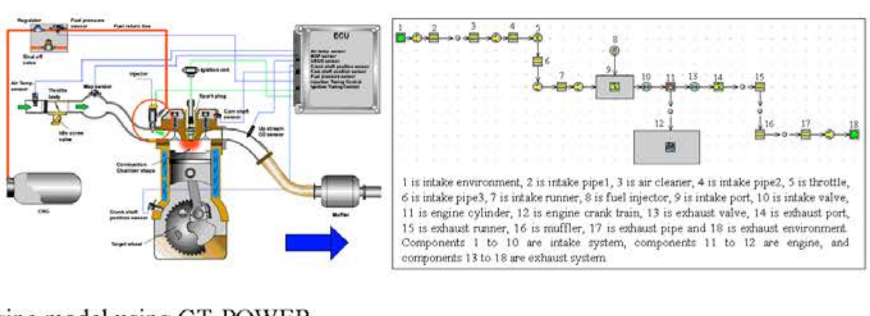

Fig. 2: CNG engine model using GT-POWER

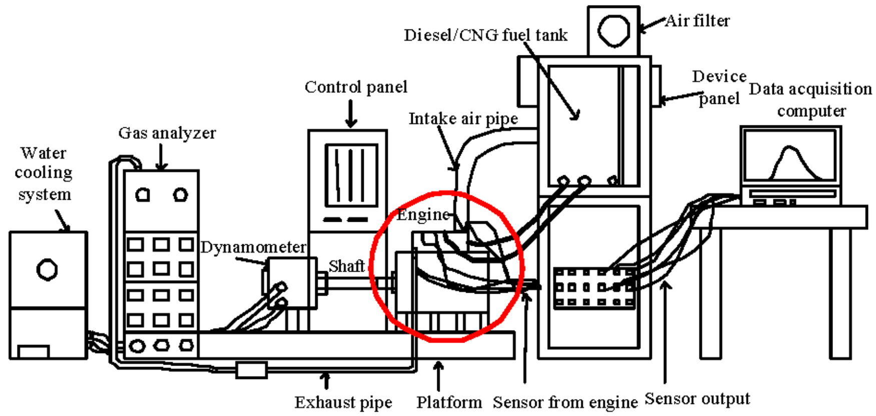

Fig. 3: Schematic of engine experimental set-up

period of time that a loaded engine requires for the crankshaft speed to reach steady-state. The engine cylinder pressure characteristics calculation is according to Heywood (1998).

Experimental method: The experimental investigation of the diesel engine pressure performance is using Dewetron Dewe5000 computational combustion analyzer. This is the basic step of the research and conducted to collect data for engine pressure performances as baseline reference before converted to CNG engine. The experiment set-up is shown in Fig. 3.

The port injection dedicated CNG engine is converted from diesel engine. To develop the port injection dedicated CNG engine, there is need of any new components or new design and modification components. The components affecting will be design and development in this research are piston, spark ignition, natural gas fueling system and electronic control unit. The research design and development of components affecting for CNG engine is based on CNG engine computational modeling performance data, then the best performance data is used to design and development the physically components affecting. The piston engine is modified component in the engine and designed to decrease the compression ratio from base diesel engine and develop using CNC machine. The spark ignition is new component in the engine and designed for assist the CNG engine combustion, the location of the spark plug is using the hole of the injector and modified in size of geometries. The natural gas fueling system is new fueling system in the engine to change the liquid fueling system and designed based on sequential injection natural gas, where the system start from cylinder tank, pressure regulator, solenoid and injector. In the sequential injection, the injector is located in the intake port before intake valve in every engine cylinder. The natural gas fueling system is operated using electronic system. The electronic control system is new component to change the mechanical system in the base diesel engine. The electronic control system is to manage the injection timing, spark timing and engine combustion. The experimental of port injection CNG engine spark ignition is to investigate the performance and exhaust gas emissions effect. The experimental is using Dewetron Dewe5000 computational combustion analyzer and engine control data acquisition. The engine control and data acquisition is used to investigate the in-cylinder pressure and Crank Angle (CA) degree.

RESULTS

The results of cylinder pressure performance of direct injection diesel engine, compression ratio modified direct injection diesel engine and port injection dedicated CNG engine are shown in Fig. 4-11.

Engine cylinder pressure profile: The engine cylinder pressure profile investigation results are shown in Fig. 4-10. The results are shown that the cylinder pressure is increasing in compression stroke to combustion ignition in crank angle negative180° Bottom Dead Center (BDC) until around in crank angle 0° Top Dead Center Force (TDCF). In the compression stroke, the air-fuel volume is compressed from BDC to TDC. The simulation and experiment results are not similar. The simulation results are higher than the experimental results. The deviation is in average 2% for CNG engine (CNGE) and diesel engine (ODE). The compression ratio of direct injection diesel engine is 20.28:1, the compression ratio of modified direct injection diesel

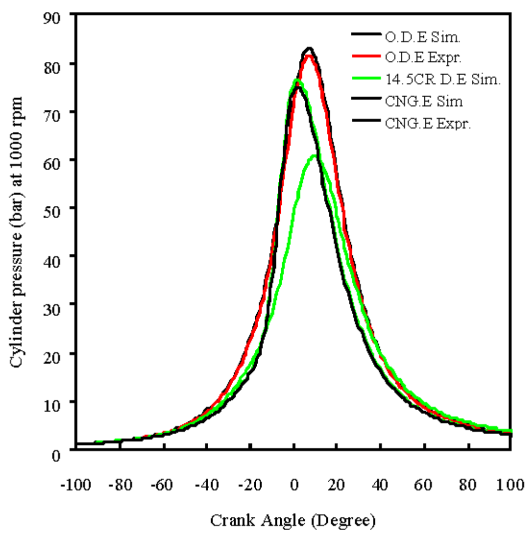

Fig. 4: Cylinder pressure at 1000 rpm

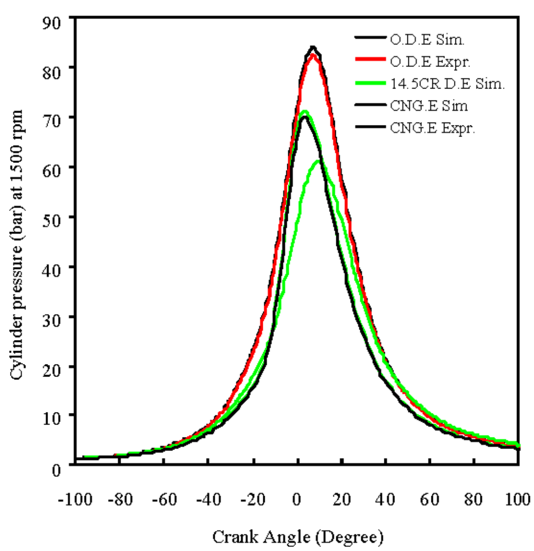

Fig. 5: Cylinder pressure at 1500 rpm

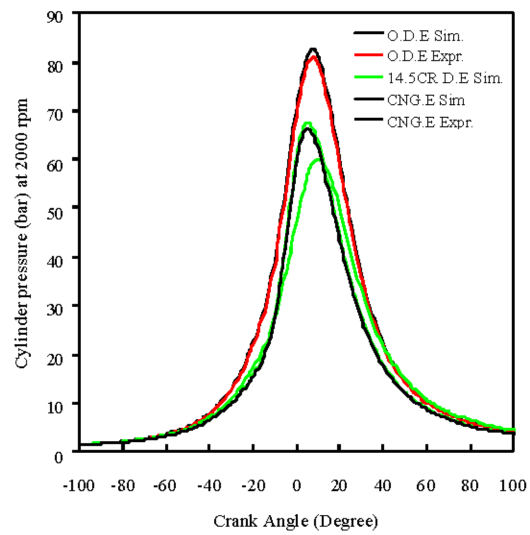

Fig. 6: Cylinder pressure at 2000 rpm

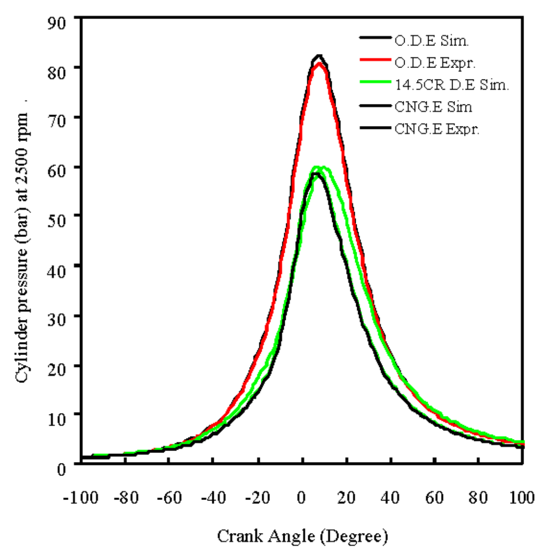

Fig. 7: Cylinder pressure at 2500 rpm

engine is 14.5:1 and the that the direct injection diesel engine cylinder pressure is higher than the modified direct injection diesel engine and port injection dedicated CNG engine. The highest of cylinder pressure is around in crank angle 0 degree (TDCF). From the cylinder pressure performance can be predicted that the product of engine power from the air-fuel combustion of direct injection diesel engine is higher than modified direct injection diesel engine and the port injection dedicated CNG engine. The direct injection diesel engine cylinder pressure is higher than modified direct injection diesel engine and port injection dedicated CNG engine because the compression ratio of diesel engine is higher.

Engine cylinder maximum pressure profile: The highest of maximum cylinder pressure in the combustion process both of diesel engines are shown in Fig. 5 and for port injection dedicated CNG engine is shown in Fig. 4. In the diesel engine, the maximum cylinder pressure is 84.0 bar declared in 1500 rpm engine speed. In the modified diesel engine, the maximum cylinder pressure is 61.1 bar declared in 1500 rpm engine speed. In the port injection dedicated

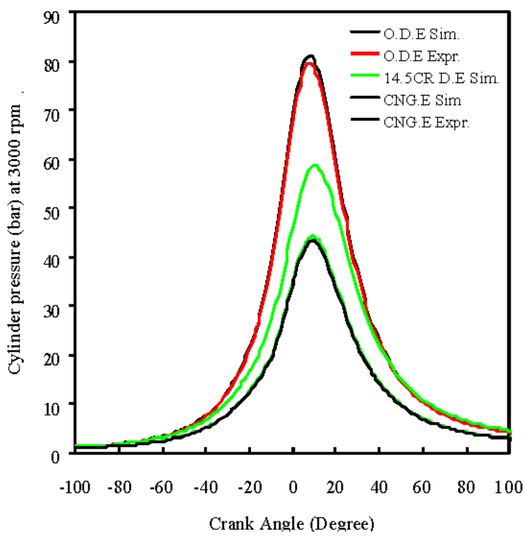

Fig. 8: Cylinder pressure at 3000 rpm

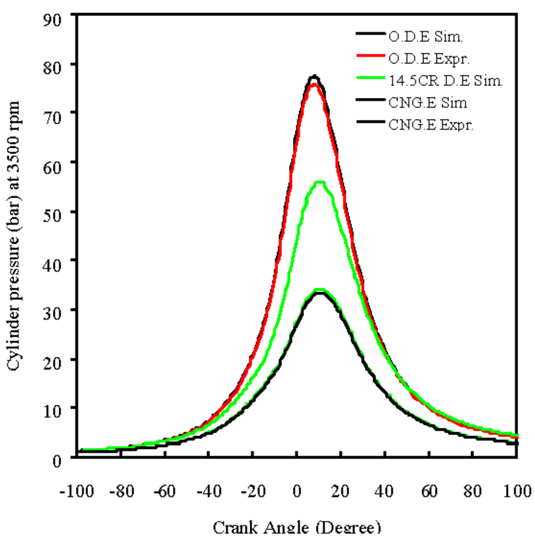

Fig. 9: Cylinder pressure at 3500 rpm

CNG engine, the maximum cylinder pressure is 76.23 bar and declared in 1000 rpm engine speed. In this operating condition, both of diesel engines and CNG engine combustion process are most excellent than the other condition. In the diesel engine, the 1500 rpm engine speed condition is not higher and not lower for the combustion of diesel fuel. Burned diesel fuel rate in 1500 rpm is most excellent to product the higher pressure and power. In the port injection dedicated CNG engine, the 1000 rpm engine speed condition is not higher and not lower for the combustion of CNG engine. Burned CNG fuel rate in 1000 rpm is most excellent and product the higher

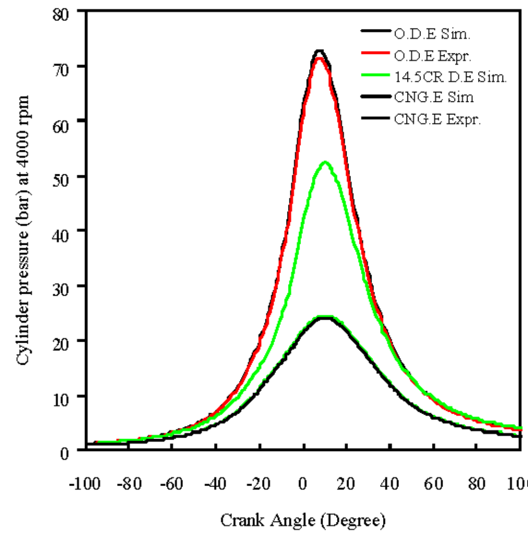

Fig. 10: Cylinder pressure at 4000 rpm

pressure and torque of the engine. The trend of the maximum cylinder pressure for direct injection diesel engine, modified direct injection diesel engine and port injection dedicated CNG engine are decreased if the engine speed is increased.

Figure 10 shows the lowest of maximum cylinder pressure of direct injection diesel engine, modified direct injection diesel engine and port injection dedicated CNG engine. The lowest maximum cylinder pressure in combustion process of direct injection diesel engine, modified direct injection diesel engine and port injection dedicated CNG engine are shown in 4000 rpm engine speed and the nominal is 72.82 bar for diesel engine, 52.29 bar for modified diesel engine and 25.00 bar for port injection dedicated CNG engine. In this case, the combustion of diesel engines and CNG engine are in lately so the combustion process is not excellent and unburned fuel is highest, this phenomenon can be decreasing the engine cylinder pressure performance. The port injection dedicated CNG engine maximum cylinder pressure is lowest because the natural gas fuel is lower in density, hydrocarbon and energy than the diesel fuel. So, the cylinder pressure in the same compression ratio, the CNG engine is lower than the modified diesel engine if the engines are operated in high speed. The lowest cylinder pressure of diesel engine is higher than modified diesel engine because the compression ratio of diesel engine is higher than modified diesel engine.

DISCUSSION

The maximum cylinder pressure effect of the diesel engine converted to port injection dedicated CNG engine in variation engine speed is shown in Fig. 11.

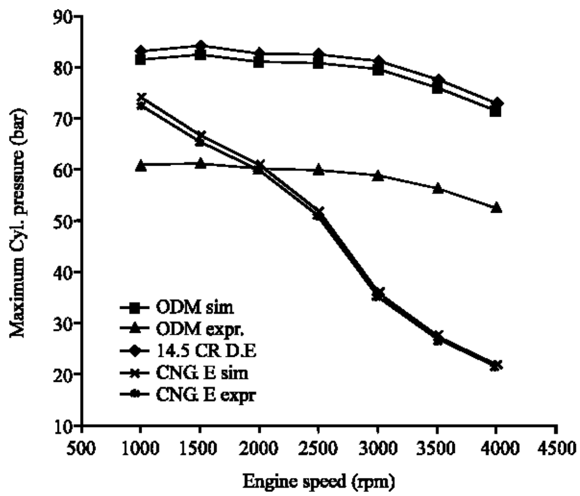

Fig. 11: Maximum cylinder pressure

In the 1000 rpm engine speed, the conversion of diesel engine to CNG engine is increase the maximum cylinder pressure 21.70%. In the 1500 rpm engine speed, the conversion of diesel engine to CNG engine is increase the maximum cylinder pressure 8.97%. In the 2000 rpm engine speed, the conversion of diesel engine to CNG engine is decrease the maximum cylinder pressure 1.70%. In the 2500 rpm engine speed, the conversion of diesel engine to CNG engine is decrease the maximum cylinder pressure 13.53%. In the 3000 rpm engine speed, the conversion of diesel engine to CNG engine is decrease the maximum cylinder pressure 39.12%. In the 3500 rpm engine speed, the conversion of diesel engine to CNG engine is decrease the maximum cylinder pressure 51.40%. At the 4000 rpm, the conversion is decrease maximum cylinder pressure 58.56%.

The maximum cylinder pressure for CNG engine is lower than the diesel engine. It caused the compression ratio of CNG engine is lower than the diesel engine and the combustion energy output of diesel fuel is produces highest power than the natural gas fuel. Another that, the density of natural gas fuel is lower than the diesel fuel. So, in the same volume, the diesel fuel is has higher pressure than the gas fuel. In this engine conversion, the CNG engine better to operate at low speed. In the low speed the maximum cylinder pressure increasing is higher dramatically than at the medium and high speed. For all of engine speed, the conversion of modified diesel engine to CNG engine is increase the cylinder pressure in low speed, but in the high speed the engine conversion can be decreasing the cylinder pressure. In the high speed CNG engine, the fuel energy is reduced and the combustion is not completely, but in the low speed the combustion of CNG engine is completely because the combustion ignition is assisted by spark plug system and the ignition point of natural gas fuel is higher than the diesel fuel, it can be producing higher engine cylinder pressure.

CONCLUSION

Diesel engine cylinder pressure is higher than modified direct injection diesel engine and port injection dedicated CNG engine because the compression ratio of diesel engine is higher. The maximum cylinder pressure for direct injection diesel engine, modified direct injection diesel engine and port injection dedicated CNG engine are decrease if the engine speed is increased. The lowest cylinder pressure of diesel engine is higher than modified diesel engine because the compression ratio of diesel engine is higher than modified diesel engine. The maximum cylinder pressure for CNG engine is lower than the diesel engine. It caused the compression ratio of CNG engine is lower than the diesel engine and the combustion energy output of diesel fuel is produces highest power than the natural gas fuel.

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