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Engine Cylinder Fluid Characteristics of Diesel Engine Converted to CNG Engine

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Abstract

This research has investigated the fluid characteristic effect in the engine cylinder of four-stroke direct injection diesel engine converted to port injection dedicated compressed natural gas (CNG) engine spark ignition. This research has using computational engine model for steady-state and transient simulation. The investigation and simulation of the engine cylinder flow performance characteristic profile based on engine computational model. The engine computational model has developed based from the diesel engine converted to port injection dedicated compressed natural gas (CNG) engine spark ignition. The simulation of engine model has simulated in variations engine speeds. The simulation results of fluid characteristics are shown the characteristics of in cylinder volumetric efficiency profile, percent burned mass, fuel/air ratio, fuel flow profile, total fuel consumption and total fuel energy entering to cylinder in variations engine speeds.

Keywords: CNG engine, computational model, diesel engine, engine cylinder, fluid characteristics.

Introduction

Steady state and transient simulation of gas flow in engine cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine in this research is using GT-Power software. This research is focuses on cylinder volumetric efficiency profile, percent burned mass at cycle start, fuel/air ratio, fuel flow profile, total fuel consumption and total fuel energy entering cylinder in variations engine speeds of single cylinder four stroke port injection dedicated compressed natural gas (CNG) spark ignition engine. The objective is to give an insight into the engine cylinder gas flow thermodynamics performance using GT-Power simulation model, how the engine model developed and how the components interaction.

Port injection dedicated compressed natural gas (CNG) spark ignition engine has an injector for each cylinder, so the injectors can be placed in close proximity to the cylinder's intake port. It also enables fuel to be delivered precisely as required to each individual cylinder (called sequential) and enables more sophisticated technologies such as skip-firing to be used. Skip-firing is when only some of the cylinders are operating and the other cylinders are being skipped. This enables even more efficient use of the fuel at low loads, further lowering fuel consumption and unburned hydrocarbon emissions (Bakar *et al.*, 2007; Cho and He, 2007; Czerwinski *et al.*, 1999; Kato *et al.*, 1999; Klein and Ericksson, 2002; Sera *et al.*, 2003). Gas fuel usually injected at high velocity as one or more jets through small orifices or nozzles in injector tip, via intake port into the combustion chamber. The gas fuel mixes with high temperature and high pressure air in cylinder. The air is supplied from intake port of engine too. Since the air and gas temperature and pressure are near the ignition point, spark ignition of portions of the already-mixed gas 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 (Blair, 1999; Challen and Baranescu, 2003; Sera *et al.*, 2003).

Problem in spark ignition CNG engine combustion chamber design is achieving sufficiently rapid mixing between the injected gas fuel and the air from intake port in the cylinder to complete combustion in the appropriate crank angle interval close to top-center (Bakar *et al.*, 2007b; Bakar *et al.*, 2007c; Cho and He, 2007; Hollnagel *et al.*, 1999; Sera *et al.*, 2003; Shashikantha and Parikh, 1999). Horsepower output of an engine can be dramatically improved through the good intake port design and manufacture (Jawad and Dragoiu, 2003).

Fluid Characteristics Parameter in the Engine Cylinder

To investigate the flow conditions right in the engine cylinder is the essence of modeling at small intervals time. Flow condition in the engine cylinder simulation using GT-Power is basically air and fuel from intake valve, volumetric efficiency profile, percent burned mass at cycle start, fuel/air ratio, fuel flow profile, total fuel consumption and total fuel energy (Gamma Technologies, 2003). The core of any model is the energy equation for each performance is shown in equation (1) – equation (12).

Cylinder Volumetric Efficiency: By using the cylinder volumetric efficiency reference in the GT-Power computational numerical analysis, the ambient indicates that the volumetric efficiency map data is referenced to a constant reference condition, usually ambient (Gamma Technologies, 2003). If this option is selected, the mass flow through the cylinder will be calculated from the map using the pressure, temperature, and composition defined in the reference state for ambient volumetric efficiency. The reference object that is used to specify the pressure, temperature, and composition that should be used for volumetric efficiency calculations. If the volumetric efficiency map reference state above is set to ambient, this reference state will be used along with the volumetric efficiency map to determine the imposed air mass flow through the cylinder. The conditions specified in this object usually correspond to the ambient conditions, but may alternatively be any constant reference state. Cylinder volumetric efficiency is calculated using equation (1).

$$volefca = \oint \frac{\dot{m}_{ub,nf}\, dt}{\rho_{ref} V_{disp}} \tag{1}$$

where, *volefca* is in cylinder volumetric efficiency, $\dot{m}_{ub,nf}$ is instantaneous mass flow rate of unburned non-fuel gases past all intake valves in kg/s, ρ_{ref} is density calculated reference object pointed from the engine cylinder attribute reference state for volumetric efficiency in kg/m^3, where ambient conditions are most typically specified. *Vdisp* is engine cylinder displacement volume in m^3.

Percent Burned Mass at Cycle Start: If the $m_{b,i,cs}$ is mass of burned gas trapped in cylinder i at the start of cycle for cylinder i in kg, $m_{tot,i,cs}$ is total mass trapped in cylinder i at the start of cycle for cylinder i in kg. The calculation of percent burned mass at cycle start is given in equation (2).

$$burnmfcs = \left[\frac{m_{b,i,cs}}{m_{tot,i,cs}}\right] x100 \qquad (2)$$

Unburned Non-Fuel Gas Flow Past Intake Valve: In calculation of unburned non-fuel gas flow past intake valve is calculated from mass flow rate past intake valves. If the *airin* is unburned non-fuel gas flow past intake valve, $\dot{m}_{ub,nf}$ is instantaneous mass flow rate of unburned non-fuel gas past all intake valves in kg/s, the equation to calculate the unburned non-fuel gas flow past intake valve is using the equation (3).

$$airin = \left[\oint \dot{m}_{ub,nf}\, dt\right] x10^{6} \qquad (3)$$

Trapped Unburned Non-Fuel Gas: The trapped unburned non-fuel gas at cycle start (*traircs*) will differ from unburned non-fuel gas flow past intake valves in cases where significant blow-through during the valve overlap period is observed.

$$traircs = airin \qquad (4)$$

Cylinder Trapping Ratio: Cylinder trapping ratio is nominal of trapped unburned non-fuel gas at cycle start compare with unburned non-fuel gas flow past intake valve. If the trappc is cylinder trapping ratio identity, the calculation of trappc can be determined using equation (5).

$$trappc = \frac{traircs}{airin} \qquad (5)$$

Fuel Flow Past Intake Valves: The fuel flow past intake valves is the fuel flow rate were enter to engine cylinder via intake port. If the fuel flow past intake valves is fuelman, to calculate the fuel flow past intake valves is using equation (6).

$$fuelman = \left[\oint \dot{m}_{fuel,iv}\, dt\right] x10^{6} \qquad (6)$$

where, $\dot{m}_{fuel,iv}$ is instantaneous mass flow rate of fuel past all intake valves in kg/s.

Trapped Fuel at Cycle Start: The trapped fuel at cycle start will differ from fuel flow past intake valves in cases where significant blow-through during the valve overlap period is observed. If the trfuelcs is trapped fuel at cycle start, the nominal can be calculated using equation (7).

$$trfuelcs = fuelman \qquad (7)$$

Total Fuel Consumption: The total fuel (fueltott) in cylinder will differ from fuel flow past intake valves in cases where significant blow-through during the valve overlap period is observed. In the sequential injection, the fuel enter to engine cylinder is from intake valves only, so the fuel injected direct to engine cylinder value is zero. To calculate total fuel consumption is using equation (8)

$$fueltott = fuelman \qquad (8)$$

Fuel/Air Ratio: The fuel/air ratio (farat) in engine cylinder is total fuel per trapped air. To calculate fuel/air ratio is using equation (9).

$$farat = \frac{fueltott}{traircs} \qquad (9)$$

Fuel/Air Ratio at Cycle Start: The fuel/air ratio at cycle start (facs) is the nominal of trapped fuel at cycle start per trapped unburned non-fuel gas at cycle start, the calculation is using equation (10).

$$facs = \frac{trfuelcs}{traircs} \qquad (10)$$

Effective Fuel/Air Ratio: The effective fuel/air ratio is the reconstituted fuel/air ratio of all chemical species in the cylinder just prior to the opening of the first exhaust valve. Of the three engine cylinder RLT variables that describe fuel/air ratio, effective fuel/air ratio is the most representative of the mixture exiting the cylinder, because it accounts for all of the chemical species including EGR and residual gas that take part in combustion. The other two variables, fuel/air ratio and fuel/air ratio at cycle start, are simply ratio's of fuel and air flow, they do not account in any way for the presence of EGR in the cylinder at the beginning of combustion.

Total Fuel Energy Entering Cylinder: The total fuel energy entering the engine cylinder can be calculate based from fuel lower heating value and mass flow rate of fuel crossing cylinder. The calculation of total fuel energy entering cylinder can be calculated using equation (11).

$$fuelnrg = \left(LHV_f\right)\oint \dot{m}_{f,i,gas}\, dt \qquad (11)$$

where, the LHV_f is fuel lower heating value in J/kg, $\dot{m}_{f,i,gas}$ is instantaneous mass flow rate of fuel crossing cylinder *i* control volume in gaseous state in kg/s, *nr* is revolutions per cycle, 1 for 2 stroke, 2 for 4 stroke.

Percent Burned Mass at Cycle Start: If the $m_{b,i,cs}$ is mass of burned gas trapped in cylinder i at the start of cycle for cylinder i in kg, $m_{tot,i,cs}$ is total mass trapped in cylinder i at the start of cycle for cylinder i in kg. The calculation of percent burned mass at cycle start is given in equation (12).

$$burnmfcs = \left[\frac{m_{b,i,cs}}{m_{tot,i,cs}}\right]x100 \qquad (12)$$

Engine Computational Model Development

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 (Bakar *et al.*, 2007b; Bakar *et al.*, 2007c; Ismail *et al.*, 2007; Semin *et al.*, 2007a – 2007d, 2008) 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 (Gamma Technologies, 2003). Engine parameters are shown in Table 1.

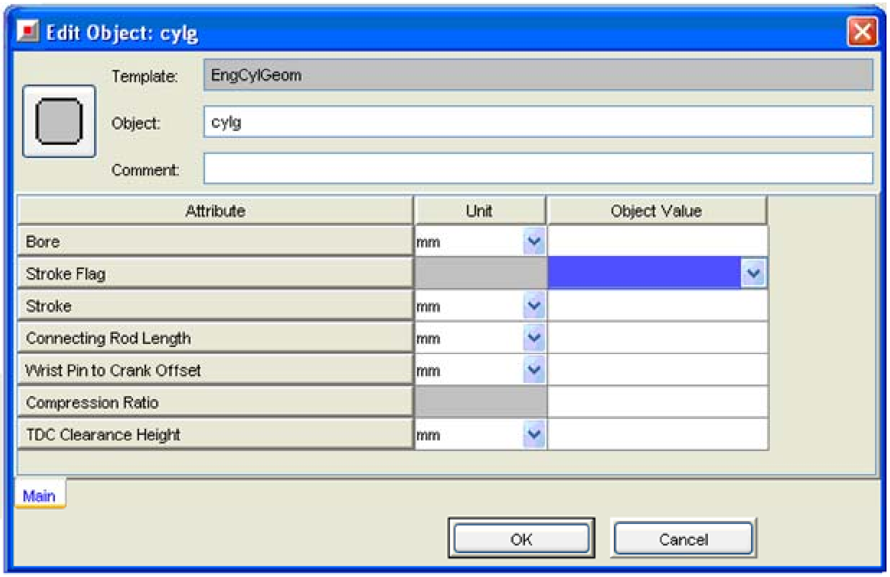
Table 1: Specification the engine

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

Port injection dedicated compressed natural gas (CNG) spark ignition engine model is based from diesel engine components data. All of the diesel engine components data are input to the window libraries of every components engine model, the example of window library is shown in Figure 1.

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 Figure 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. 9 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.

Figure 1: Window library for input data the engine cylinder geometry



Edit Object: cylg

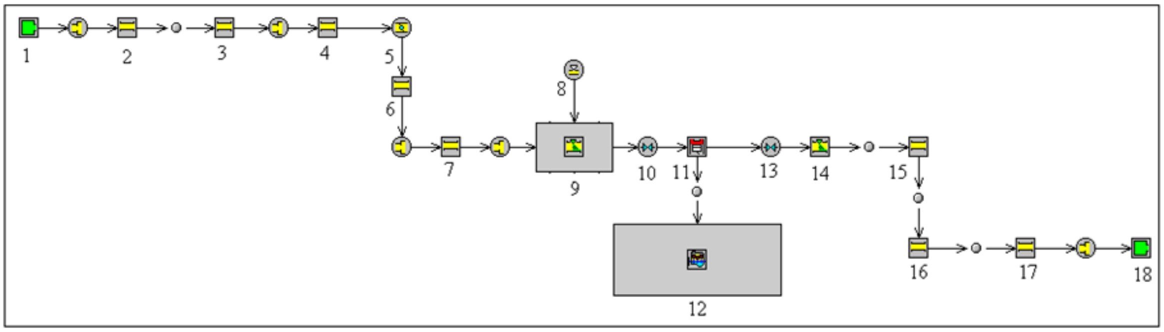
Template: EngCylGeom

Object: cylg

Comment:

Attribute	Unit	Object Value
Bore	mm	
Stroke Flag		
Stroke	mm	
Connecting Rod Length	mm	
Wrist Pin to Crank Offset	mm	
Compression Ratio		
TDC Clearance Height	mm	

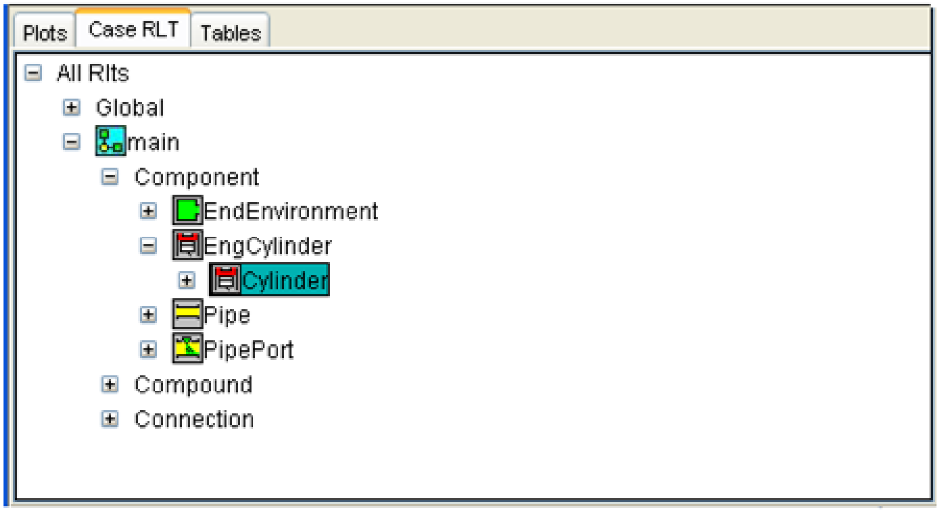
Figure 2: Sequential injection CNG engine computational model using GT-POWER



where, 1 is intake environment, 2 is intake pipe1, 3 is air cleaner, 4 is intake pipe2, 5 is throttle, 6 is intake pipe3, 7 is intake runner, 8 is fuel injector, 9 is intake port, 10 is intake valve, 11 is engine cylinder, 12 is engine crank train, 13 is exhaust valve, 14 is exhaust port, 15 is exhaust runner, 16 is muffler, 17 is exhaust pipe and 18 is exhaust environment. Components 1 to 10 are intake system, components 11 to 12 are engine, and components 13 to 18 are exhaust system.

Solver menu of GT-POWER is shown in Figure 3. The solver in this research is determines the performance of an engine model simulation based on engine speed mode in the EngineCrankTrain object (Gamma Technologies, 2003). Speed mode is the most commonly used mode of engine simulation, especially for steady states cases (Blair, 1999; Gamma Technologies, 2003). In the research imposes the engine speed 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 period of time that a loaded engine requires.

Figure 3: Post processing result menu



Result and Discussion

Characteristics of air-fuel as a fluid in engine cylinder of four stroke port injection dedicated compressed natural gas (CNG) spark ignition engine simulations results are volumetric efficiency profile, percent burned mass at cycle start, fuel/air ratio, fuel flow profile, total fuel consumption and total fuel energy, were resulted from GT-Post post processing caseRLT. The air-fuel characteristics of the port injection dedicated compressed natural gas (CNG) spark ignition engine are compared with the base diesel engine as a basic engine before convert to CNG engine. The fluid in engine cylinder characteristics comparison of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine is based on variations engine speeds.

The air-fuel in engine cylinder characteristic is shown in Figure 4 – Figure 9. The results investigation is focuses in air-fuel in cylinder characteristics profile of port injection dedicated compressed natural gas (CNG) spark ignition engine and original diesel engine in any cases engine speeds. Figure 4 shows the cylinder volumetric efficiency of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine in 1000 - 4000 rpm engine speeds. Figure 5 shows the percent burned mass at cycle start in engine cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine in 1000 - 4000 rpm engine speeds. Figure 6 shows the minimum pressure inlet and outlet at intake shows the fuel/air ratio in engine cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine in 1000 - 4000 rpm engine speeds. Figure 7 shows the fuel flow past intake valve to cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine in 1000 - 4000 rpm engine speed. Figure 8 shows the total fuel consumption per cycle of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine in 1000 - 4000 rpm engine speed and Figure 9 shown the total fuel energy entering engine cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine in 1000 – 4000 rpm engine speed.

The volumetric efficiency in engine cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine characteristics is shown in Figure 4. The performance data results are collected in 1000 – 4000 rpm engine speed. The diesel engine volumetric efficiency is higher than the port injection dedicated compressed natural gas (CNG) spark ignition engine. The performance trend both of the engine is same profile. Increasing the engine speed will be decrease the volumetric efficiency in cylinder. In engine cylinder operational, if the engine speed is increased the mass flow rate of unburned non-fuel gases past all intake valves will be decrease, so the volumetric efficiency will be decrease too.

Figure 5 shows the percent burned mass at cycle start characteristics both of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine. The percent of burned mass at cycle start of port injection dedicated compressed natural gas (CNG) spark ignition engine is higher than diesel engine. The trend of the percent burned mass at cycle start characteristics is shown in Figure 5, where increasing the engine speed from 1000 rpm to 4000 rpm will be increase the percent burned mass at cycle start. It means that the increasing mass of burned gas trapped in cylinder at the start of cycle in cylinder is higher than total mass trapped in cylinder if the engine speed is increased.

Fuel/air ratio in cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine and diesel engine are shown in Figure 6. The increasing of engine speed will be increase the fuel/air ratio in cylinder. The nominal of fuel/air ratio in cylinder diesel engine is higher than the port injection dedicated compressed natural gas (CNG) spark ignition engine. The increasing phenomenon in diesel engine is dramatically compared with port injection dedicated compressed natural gas (CNG) spark ignition engine, where increase in slowly trend. The fuel/air ratio in cylinder in port injection dedicated compressed natural gas (CNG) spark ignition engine is lower because the CNG fuel as a gas properties, so the trapped in engine cylinder is lower than diesel fuel as a liquid fuel and increasing the engine speed in port injection dedicated compressed natural gas (CNG) spark ignition engine will be decrease the cumulative mass injection fuel of injector to intake valve and enter to engine cylinder.

Fuel flow profile of fuel flow past intake valve to cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine in 1000 - 4000 rpm engine speed is shown in Figure 7. The highest of fuel flow past intake valve to cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine is in low engine speed and the lower in high engine speed. It meant that increasing engine speed will be decrease the fuel flow past intake valve to cylinder of port injection dedicated compressed natural gas (CNG) spark ignition engine. In the port injection dedicated compressed natural gas (CNG) spark ignition engine, if the engine is decrease the engine speed, the consumption gas fuel will be economically in 1000 rpm - 4000 rpm engine speed.

The total fuel consumption per cycle of port injection dedicated compressed natural gas (CNG) spark ignition engine is lower than diesel engine. The total fuel consumption per cycle in diesel engine is fixed or not decreasing or increasing if the engine speed is decrease or increase, because the injector in diesel engine is set in fixed 17.5 mg/cycle. However, the port injection dedicated compressed natural gas (CNG) spark ignition engine is not equal with diesel engine, where the increasing engine speed will gives some effect in total fuel consumption per cycle. The increasing engine speed will be decrease the total fuel consumption per cycle, because in this case the fuel mass flow rate to engine cylinder is decrease. Total fuel consumption per cycle shown in Figure 8.

The total fuel energy entering cylinder of diesel engine is higher then the sequential injection CNG engine. The characteristics are shown in Figure 9. Based on fuel consumption, the diesel engine is higher then the port injection CNG engine. The total fuel consumption of diesel engine is fixed in 17.5 mg/cycle, so it can be produce the stabile energy product. In the port injection CNG engine, the total fuel consumption at cycle start is decrease if the engine speed is increasing. So, the effect is the engine produce the lower energy than the diesel engine.

Figure 4: Cylinder volumetric efficiency

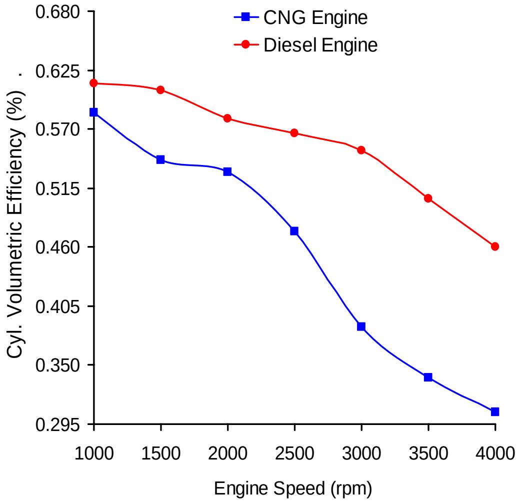


Figure 5: Percent burned mass at cycle start

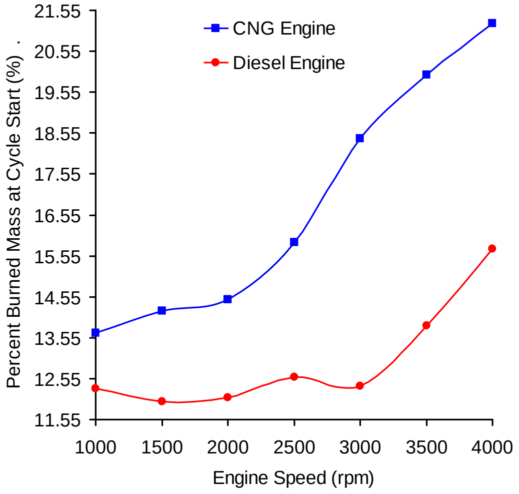


Figure 6: Fuel/air ratio in cylinder

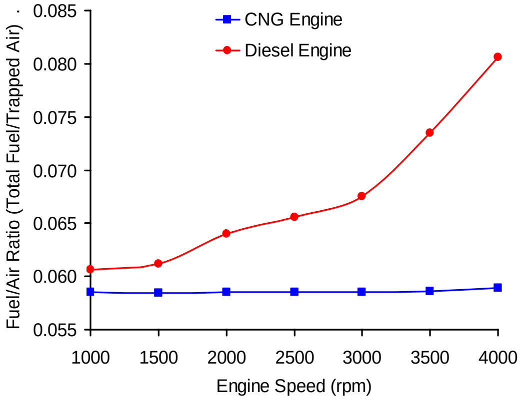


Figure 7: Fuel flow past intake valve to cylinder of sequential injection CNG engine

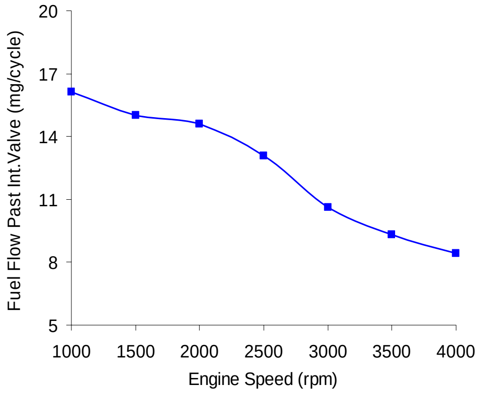


Figure 8: Total fuel consumption per cycle

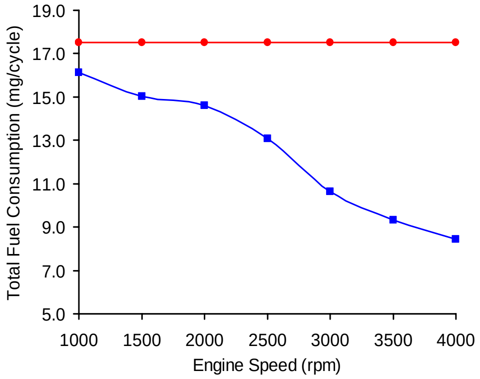
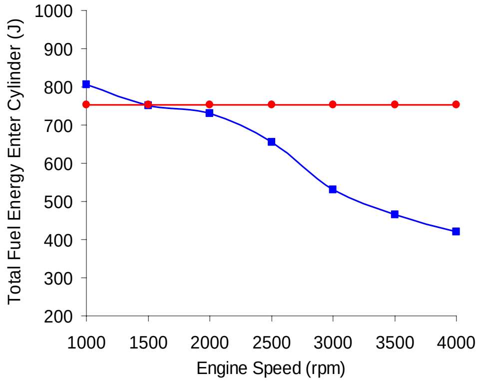


Figure 9: Total fuel energy entering cylinder



Conclusion

Fluid characteristics of port injection dedicated compressed natural gas (CNG) engine has investigated. The air-fuel characteristics results shown that increasing engine speed in port injected CNG engine will be decrease the air-fuel characteristics such as cumulative mass fuel injected, cylinder volumetric efficiency, Fuel flow past intake valve to cylinder, total fuel consumption per cycle and total fuel energy entering cylinder. Another that, the that increasing engine speed in port injected CNG engine will be increase the air-fuel characteristics such as mass flow rate from intake valve, percent burned mass at cycle start and fuel/air ratio in cylinder. The air-fuel performance characteristics in cylinder of port injection CNG engine commonly is lower than the base diesel engine, but the percent burned mass at cycle start is higher than diesel engine. It means that conversion of diesel engine to port injection CNG engine commonly will be reduce the air-fuel characteristics in cylinder and increase the percent burned mass at cycle start.

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