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Investigation of Torque Performance Effect on the Development of Sequential Injection CNG Engine

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Abstract: This research explores the effect of diesel engine convert to sequential or multi point injection dedicated CNG engine. The engine conversion is by modification and reduce the piston compression ratio, change the fuel system from mechanical system to ECU system, added the spark ignition system and intake air throttle. In this research, the effect of diesel engine convert to CNG engine is investigated based on engine speed variation. The engine speeds variation is 1000 to 4000 rpm with variation in 500 rpm. This engine conversion and torque performance effect investigation is conducted at Automotive Laboratory, Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia. The engine conversion effect is reduce the engine torque performance. Another is that, the increasing engine speeds can be increase the deviation of engine torque performance of diesel engine compared CNG engine.

Key words: CNG engine development, engine speed variation effect, torque performance effect

INTRODUCTION

Nowadays, the alternative fuel has 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 increase. In the other hand, fossil fuel has contributed a large pollution. Both derivatives from the hydrocarbon fuel itself like carbon dioxides and impurities like heavy metals, sulfur and uranium contribute to the pollution. Natural gas as alternative fuel is becoming increasingly important in the transport sector (Aslam *et al*., 2006). The exploitation of full potential of alternative fuels, as means of reducing exhaust emissions irrespective of whether they are renewable or not requires dedicated engines rather than retrofitted ones, or bi-fuels ones or dual-fuels ones. Obviously, a dedicated engine requires extra cost compare to retrofitted or other type of natural gas vehicles and also require adequate fuel distribution network. Its makes the dedicated engine uncompetitive and impractical at the present days based on economic cost. However, as the liquid fossil fuels will be finished, the research of applying natural gas fuel on internal combustion engine or vehicle will be an important activity (Cho and Bang-Quan, 2007; Marie, 2007).

However, CNG application has some advantages compared to diesel from an environmental perspective. It is a cleaner fuel than either diesel as far as emissions are concerned. CNG is considered to be an environmentally clean alternative to those fuels (Xu *et al*., 2005; Shiga *et al*., 2002). According to Ganesan (1999), some advantages of compressed natural gas as a fuel are octane number is very good for SI engine fuel. Where, octane number is a fast flame speed, so engines can be operate with a high compression ratio, less engine emissions, less aldehydes than methanol and the fuel is fairly abundant worldwide. The disadvantages of CNG as an alternative engine fuel is having low energy density resulting in low engine performance and low engine volumetric efficiency. Because CNG is a gaseous fuel, it is need for large pressurized fuel storage, so there is some safety concern with a pressurized fuel tank, inconsistent fuel properties and refueling of the CNG is a slow process. Several factors affecting the low engine torque are loses in volumetric efficiency, low flame speed, low compression ratio, absence of fuel evaporation and change in stoichimetric air/fuel ratio (Ganesan, 1999; Cho and Bang-Quan, 2007). In the losses in volumetric efficiency, the torque loss could be partly explained by the low density of natural gas (Srinivasan *et al*., 2006). Another that, the CNG as a gaseous fuel occupies a larger volume per unit

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energy than a liquid fuel. The natural gas in the mixture drawn into the cylinder displaces approximately 8 to 10% of oxygen available for combustion. In other words, CNG in its gaseous state decreases volumetric efficiency by the same amount and consequently reducing torque. For the flame speed, natural gas has a very low flame speed, which is much lower than gasoline. Values as much as 60% decrease in lower burning velocity for natural gas has been measured (Semin *et al*., 2008). These effect the total combustion duration prolonged compared with diesel and gasoline. With the conventional valve timing setting for liquid fuel engines, it would be impossible for CNG operation to complete the whole combustion before the exhaust valve opens, even if the gas mixture was ignited earlier. This can cause a further reduction in the engine torque output of 5 to 10%. For the Compression Ratio (CR), current gas engine practice is mainly limited to simple conversion from either gasoline or diesel engines. For gasoline engines, the CR is in the range of 8:1 to 9.5:1. On the other hand, the CNG with higher octane rating allows engine CR increase up to 15:1. Increasing the CR would partially increase ideal efficiency and the torque output (Semin *et al*., 2008). Heywood (1998) stated that for the important compression ratio range of 9 to 11 the relative efficiency improvement is between 1-3% per unit compression ratio increase, depending on cylinder size and operating conditions. Absence of fuel evaporation of CNG engine is when gasoline evaporates (required before combustion), the energy required for the phase change decrease intake charge temperature and air partial pressure (Heywood, 1998). The decrease in temperature offsets the decrease in air partial pressure and results in a positive increase to volumetric efficiency of about 2%. CNG does not evaporate before combustion, losing any potential gain from the heat vaporization.

The engine torque performance parameters of direct injection diesel fuel compared with sequential or multi point injection CNG engine spark ignition is studied in this research. If the engine is operated in engine speed (avgrpm), the Eq. 1-6 used in engine torque performance calculation. When an engine crank train part is present in the calculation, there are four different instantaneous torque quantities available. The designations given to these four instantaneous torque are indicated, crank pin, friction, shaft and brake (Heywood, 1998).

Engine indicated torque: The instantaneous indicated torque, Ti(t), represents the thermodynamic work transferred from the gas to the piston converted via geometry to a torque applied to the crankshaft. The illustration is shown in Fig. 1.

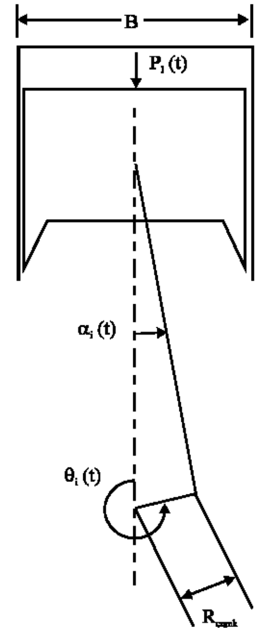

Fig. 1: Indicated torque work transfer

Equation 1 is used to calculate the engine instantaneous indicated torque:

$$T_i(t) = \sum_{i-1}^{\#cylinders} \left(\frac{\pi}{4}\right) B^2 R_{crank} \left(\Delta P_i(t) \sin\theta_i(t) - \Delta P_i(t) \cos\theta_i(t) \tan\alpha_i(t)\right) \quad (1)$$

where, Δ Pi(t) is instantaneous pressure differential across the piston (i.e., the difference between cylinder pressure and crankcase pressure for cylinder i). B is the engine cylinder bore in meter, R_{crank} is length of crank in meter, θ_i (t) is instantaneous angle of crank i in degree. $\alpha_i(t)$ is instantaneous angle of connecting rod i in degree.

Engine crank pin torque: The instantaneous crank pin torque, Tcp, differs from indicated torque in that it represents the energy remaining after accounting for the instantaneous acceleration of the engine crank slider reference object. If the engine crank train attribute crank-slider object points to an engine crank slider reference object, then the instantaneous crank pin torque will differ from the instantaneous indicated torque (however, the cycle-average crank pin torque will equal the cycle-average indicated torque during constant-speed simulations). The crank slider mechanism is assumed to be massless and crank pin torque is equal to indicated torque (Heywood, 1998). Equation 2 is used to calculate instantaneous crank pin torque:

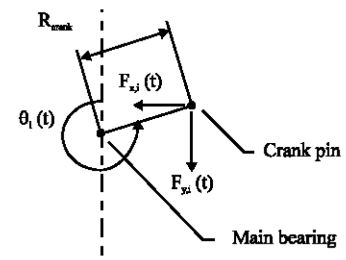

Fig. 2: Crank pin torque schematic

$$T_{cp}(t) = \sum_{i=1}^{\#cylinder} R_{crank}\left(F_{x,i}(t)\cos\theta_i(t) + F_{y,i}(t)\sin\theta_i(t)\right) \quad (2)$$

where, R_{crank} is the length of crank in meter (m), $F_{x,i}(t)$ is the instantaneous force on crank i in the x-direction in Newton (N), $F_{y,i}(t)$ is the instantaneous force on crank i in the y-direction in Newton (N) and $\theta_i(t)$ is instantaneous angle of crank i in degree (deg). The illustration is shown in Fig. 2.

Friction torque: The friction torque (ftq) is in Newtonmeter (Nm). Another is that, the friction torque for current cycle is declared using Tf(cyc). The Tf(cyc) is calculated from the engine friction reference object and is constant throughout the cycle. V_{disp} displacement volume in meter cubic (m^3), n_r is the revolutions per cycle (=1 for 2-stroke, =2 for 4-stroke). Equation 3 is used to calculate instantaneous friction torque:

$$ftq = \frac{V_{disp}(fmep)}{2\pi n_r} \times \left[10^5\right] \quad (3)$$

Shaft torque: The instantaneous shaft torque, Ts(t), represents the energy remaining after accounting for losses due to friction and attachments. The shaft torque is calculated using Eq. 4 as follows:

$$T_s(t) = T_{cp}(t) + T_a(t) - T_f(cyc) \quad (4)$$

where, $T_a(t)$ is the instantaneous torque of attachments in Newtonmeter (Nm). The T_a (t) accounts for all loads that are attached to the auxiliary port of the engine crank train part (i.e., the port number that corresponds to number-of-cylinders-plus-one). Any load attached to the load port (i.e., port 0) is not included in $T_a(t)$. $T_f(cyc)$ is the friction torque for current cycle in Newtonmeter (Nm). The $T_f(c)$ is calculated from the engine friction reference object and is constant throughout the cycle.

Brake torque: The instantaneous brake torque, $T_b(t)$, represents the torque available at the flywheel, after accounting for all friction and attachment losses as well as the acceleration of the crank train inertia. Brake torque, $T_b(t)$, is calculated using Eq. 5-6 as follows:

$$\text{Brake Torque (btq)} = \frac{\oint T_b(t)dt}{\oint dt} \quad (5)$$

$$T_b(t) = T_s(t) - I_{ct}\,\dot{\omega}_{ct}(t) \quad (6)$$

Brake torque is in Newtonmeter (Nm), I_{ct} is crank train inertia in (kg m^{-2}) and $\dot{\omega}_{ct}$ is instantaneous crank train acceleration (1/sec^2). Cycle-average values are calculated from the instantaneous crank pin, shaft and brake torque.

MATERIALS AND METHODS

The conversion development of four stroke direct injection diesel engine to sequential or multi point injection dedicated Compressed Natural Gas (CNG) engine spark ignition has studied in this research. The sequential or multi point injection dedicated CNG engine development, the engine torque performance investigation of the baseline diesel engine and sequential or multi point injection dedicated CNG engine spark ignition are conducted on 2006-2008 at Automotive Laboratory, Faculty of Mechanical Engineering, University Malaysia Pahang, Malaysia.

The diesel engine convert to multi point injection dedicated CNG engine is developed with change any components and systems. The components and systems that were changed are fuel, compression ratio, ignition system, injection system and added the throttle. The fuel in the conversion is from diesel fuel changed to natural gas. The ignition system is from compression ignition changed to spark ignition. The fuel injection system is from direct injection changed to sequential or multi point injection system. The fuel flow control is from mechanical system changed to electronic control system. The air intake system in CNG engine is using throttle to control the intake air. The direct injection diesel engine converted to sequential or multi point injection dedicated CNG engine data is shown in Table 1. In the engine conversion development, the engine is divided to the sub-systems. There are three sub-systems defined in the multi point injection dedicated CNG engine spark ignition. The first is design and development of intake system components, the second is design and development of engine cylinder and engine crank train components and the third is design and development of exhaust system components.

After the development of multi point injection dedicated CNG engine spark ignition is completed, then

Table 1: Engine conversion data

Engine parameter	Diesel engine	CNG engine
Bore (mm)	86.00	86.0
Stroke (mm)	70.00	70.0
Displacement (cc)	407.00	407.0
Compression ratio	20.28	14.5
Ignition system	Compression	Spark
Fueling system	Mechanical	Electronic controlled
Intake air	No throttle	Throttle controlled
Fuel injection system	Direct injection	Sequential injection
Fuel	Diesel	Compressed natural gas

running the engine to investigate the engine torque performance. In this investigation, the engine is running in variations engine speeds. The variation of engine speed is start from 1000 rpm until 4000 rpm with 500 rpm range.

RESULTS AND DISCUSSION

In this research, the investigation results are shown in graphs. The engine torque performance investigation results are based on variation engine speed. The torque performance results of direct injection diesel engine convert to sequential or multi point injection dedicated CNG engine are shown in Fig. 3-7. Figure 3 shows the indicated torque performance profile of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine on 1000 to 4000 rpm engine speed with range 500 rpm. Figure 4 shows the crank pin torque performance profile of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine on 1000 to 4000 rpm engine speed with range 500 rpm. Figure 5 shows friction torque of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine on 1000 to 4000 rpm engine speed with range 500 rpm. Figure 6 shows shaft torque performance profile of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine on 1000 to 4000 rpm engine speed with range 500 rpm. Figure 7 shows brake torque performance profile of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine on 1000 to 4000 rpm engine speed with range 500 rpm.

The indicated torque performance of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine is shown in Fig. 3. In the baseline diesel engine, the highest indicated torque is 24.3453 Nm and declared at 3000 rpm engine speed. The indicated torque performance profile shows that from the minimum engine speed at 1000 to 3000 rpm as the point of the highest

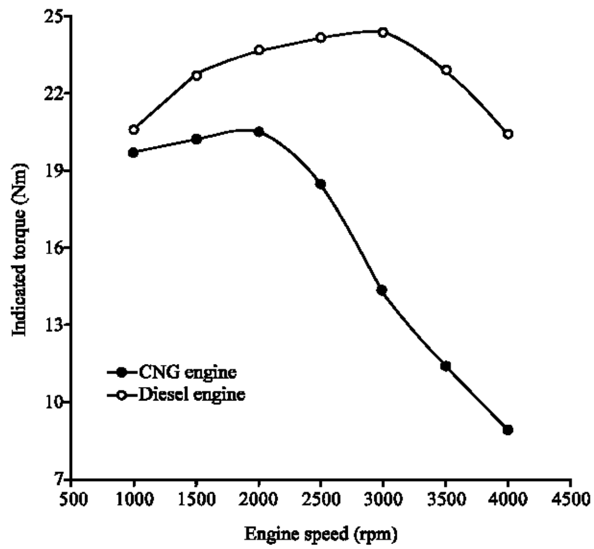

Fig. 3: Indicated torque of diesel engine compared to CNG engine in variation engine speed

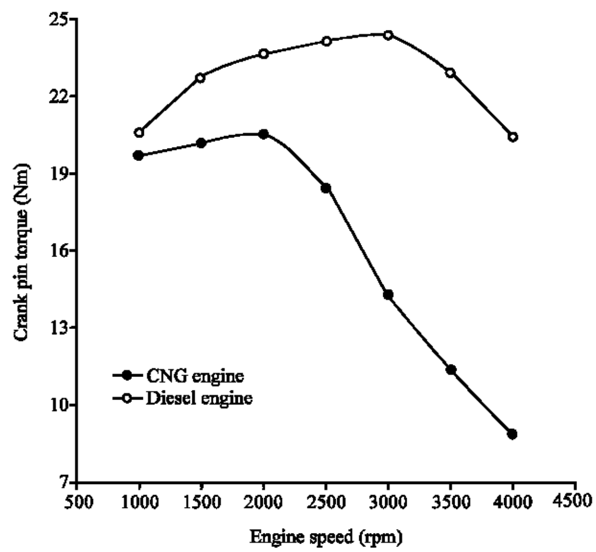

Fig. 4: Crank pin torque of diesel engine compared to CNG engine in variation engine speed

indicated torque, the indicated torque performance increase if the engine speed is increased until 3000 rpm engine speed. After 3000 rpm engine speed, the increasing engine speed can be decrease the indicated torque. In the sequential injection dedicated CNG engine, the highest indicated torque is 20.4798 Nm and declared at 2000 rpm engine speed. After 2000 rpm engine speed, the increasing engine speed can be decrease the indicated torque. Based on Fig. 3, the conversion diesel engine to CNG engine can reduce the engine torque performance. The maximum

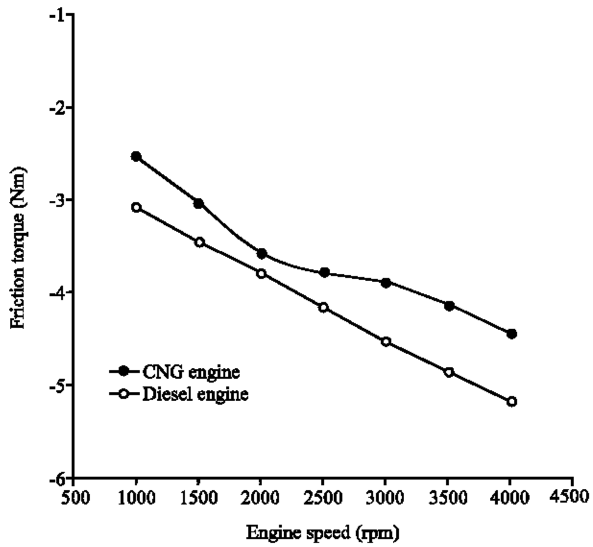

Fig. 5: Friction torque of diesel engine compared to CNG engine in variation engine speed

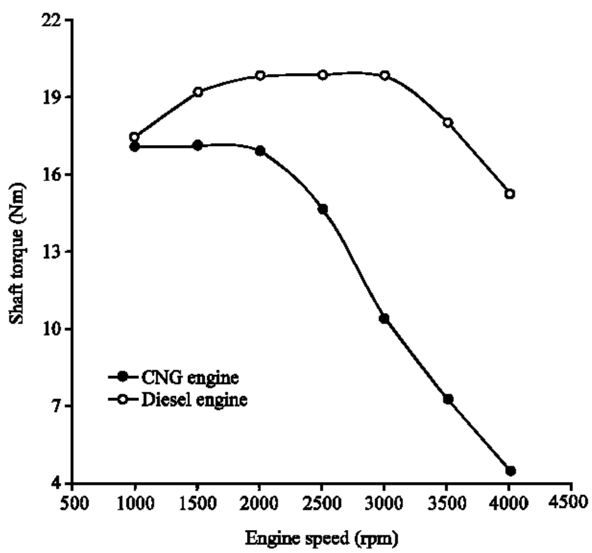

Fig. 6: Shaft torque of diesel engine compared to CNG engine in variation engine speed

indicated torque of direct injection diesel engine convert to multi point injection dedicated CNG engine is reduced 15.88%. The increasing engine speed can be increase the deviation point or percentage of the indicated torque of diesel engine compared to CNG engine. Increasing engine speed can be increase the percentage of indicated torque deviation both of engines. The increasing of indicated torque deviations are as follow. If the engine is run on 1000, 1500, 2000, 2500, 3000, 3500 and 4000 rpm, the conversion of diesel

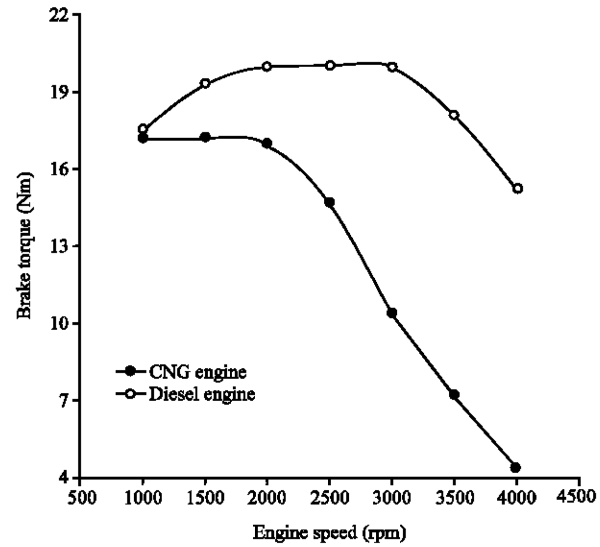

Fig. 7: Brake torque of diesel engine compared to CNG engine in variation engine speed

engine to CNG engine reduced indicated torque of 4.4, 11.08, 13.43, 23.51, 41.29, 50.34 and 56.54%.

In this engine conversion, the crank pin torque performance of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine is shown in Fig. 4. In the baseline diesel engine, the highest crank pin torque is 24.3464 Nm and declared at 3000 rpm engine speed. The crank pin torque performance profile shows that from the minimum engine speed at 1000 to 3000 rpm as the point of the highest crank pin torque, the crank pin torque performance is increase if the engine speed is increased until 3000 rpm engine speed. After 3000 rpm engine speed, the increasing engine speed can be decrease the crank pin torque. In the sequential injection dedicated CNG engine, the highest crank pin torque is 20.4808 Nm and declared at 2000 rpm engine speed. After 2000 rpm engine speed, the increasing engine speed can be decrease the crank pin torque.

According to investigation of crank pin torque performance in Fig. 4, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine can reduce the engine crank pin torque performance. The maximum crank pin torque of direct injection diesel engine convert to multi point injection dedicated CNG engine is reduced 15.88%. The increasing engine speed can be increase the deviation point or percentage of the crank pin torque of diesel engine compared to CNG engine. So, the increasing engine speed can be increase the percentage of crank pin torque deviation both of the engines. If the engine is running on 1000, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of 4.36%. If the engine is running on 1500, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of 11.08%. If the engine is running on 2000, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of 13.43%. If the engine is running on 2500, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of engine is 23.51%. If the engine is running on 3000, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of engine is 41.28%. If the engine is running on 3500, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of 50.34%. On 4000 rpm, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced crank pin torque of 56.54%.

The friction torque of multi point injection dedicated CNG engine as a new engine compared to direct injection diesel engine as a baseline engine is shown in Fig. 5. In the baseline diesel engine, the highest friction torque is negative 5.18 Nm and declared at 4000 rpm engine speed. The friction torque profile shows that from the minimum engine speed at 1000 rpm to maximum engine speed at 4000 rpm as the point of the highest indicated torque, the friction torque is increase if the engine speed is increased. In the sequential injection dedicated CNG engine, the highest friction torque is negative 4.44 Nm and declared at 4000 rpm engine speed. The friction torque profile shows that from the minimum engine speed at 1000 rpm to maximum engine speed at 4000 rpm, the friction torque is increasing. In the CNG engine and diesel engine, the friction torque is increase if the engine speed is increased. Based on Fig. 5, the conversion diesel engine to CNG engine can increase the friction torque performance. The increasing engine speed can be increase the friction torque of diesel engine compared to CNG engine.

Based on engine speed increasing, the percentage friction torque of CNG engine is higher than the diesel engine in every engine speed. If both of the engines are running in 1000 rpm, the friction torque of CNG engine is 12.83% and friction torque of diesel engine is 14.96% from the indicated torque, where in this engine speed the reducing torque of diesel engine is higher than CNG engine. If both of the engines are running in 1500 rpm, the friction torque of CNG engine is 15.02% and friction torque of diesel engine is 15.21% from the indicated torque, where in the 1500 rpm of the engine speed the reducing torque of diesel engine is exactly continue higher than CNG engine. If both of the engines are running in 2000 rpm, the friction torque of CNG engine is 17.45% and friction torque of diesel engine is 16.03% from the indicated torque, where in this engine speed the reducing torque of diesel engine is lower than CNG engine. If both of the engines are running in 2500 rpm, the friction torque of CNG engine is 20.57% and friction torque of diesel engine is 17.29% from the indicated torque, where in this engine speed the reducing torque of CNG engine is exactly continue higher than diesel engine and the percentage deviation is increased. If both of the engines are running in 3000 rpm, the friction torque of CNG engine is 27.22% and friction torque of diesel engine is 18.6% from the indicated torque, where in this engine speed the reducing torque of CNG engine is exactly continue higher than diesel engine and the percentage deviation is increased again. If both of the engines are running in 3500 rpm, the friction torque of CNG engine is 36.4% and friction torque of diesel engine is 21.23% from the indicated torque, where in this engine speed the reducing torque of CNG engine is exactly continue higher than diesel engine and the percentage deviation is increase compared to 3000 rpm. If both of the engines are running in 4000 rpm, the friction torque of CNG engine is 50.17% and friction torque of diesel engine is 25.44% rpm the indicated torque, where in this engine speed the reducing torque of CNG engine is exactly continue higher than diesel engine and the percentage deviation is increased.

The percentage deviation of friction torque compared to the indicated torque of CNG engine is lower than diesel engine in low engine speed until 1500 rpm. If the engine is running in higher than 1500 rpm engine speed, the CNG engine friction torque is higher than diesel engine. In these cases the increasing engine speed will be increase the friction torque both of the engines, but the CNG engine give the higher friction torque. It meant that the conversion of diesel engine to CNG engine can be increase the friction torque of engine. It is caused by the natural gas properties, where in the natural gas as a fuel is less or the lubrication liquid compared to diesel fuel as a liquid fuel and has the lubrication to reduce the torque.

The shaft torque performance of multi point injection dedicated CNG engine compared to direct injection diesel engine is shown in Fig. 6. In the baseline diesel engine, the highest shaft torque is 19.89 Nm and declared at 2500 rpm engine speed. The shaft torque performance profile shows that from the minimum engine speed at 1000 to 2500 rpm as the point of the highest shaft torque, the shaft torque performance is increase if the engine speed is increased until 2500 rpm engine speed. After

2500 rpm engine speed, the increasing engine speed can be decrease the shaft torque. In the sequential injection dedicated CNG engine, the highest shaft torque is 17.14 Nm and declared at 1500 rpm engine speed. After 1500 rpm engine speed, the increasing engine speed can be decrease the shaft torque. According to investigation of shaft torque performance in Fig. 6, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine can reduce the engine shaft torque performance. The maximum shaft torque of direct injection diesel engine convert to multi point injection dedicated CNG engine is reduced 13.84%. The increasing engine speed can be increase the deviation point or percentage of the shaft torque of diesel engine compared to CNG engine. So, the increasing engine speed can be increase the percentage deviation of shaft torque both of the CNG engine and diesel engine. The increasing of shaft torque deviations both of the engines based on increasing engine speeds are as follow. If both of the engines are running on 1000, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of 2%. On the 1500 rpm engine speed, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of 10.83%. If both of the engines are running on 2000, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of 14.89%. If the engines are running on 2500, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of engine is 26.43%. If the engines are running on 3000, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of engine is 47.65%. If the engines are running on 3500, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of 59.86%. On 4000 rpm engine speed, the conversion of direct injection diesel engine to multi point injection dedicated CNG engine reduced shaft torque of 70.98%.

Figure 7 shows the brake torque performance of multi point injection dedicated CNG engine compared to direct injection diesel engine. In the baseline diesel engine, the highest brake torque is 19.894 Nm and declared at 2500 rpm engine speed. The brake torque performance profile shows that from the minimum engine speed at 1000 to 2500 rpm as the point of the highest brake torque, the brake torque performance is increases if the engine speed is increased until 2500 rpm engine speed. After 2500 rpm engine speed, the increasing engine speed can be decrease the brake torque. In the sequential injection dedicated CNG engine, the highest brake torque is 17.14 Nm and declared at 1500 rpm engine speed. After 1500 rpm engine speed, the increasing engine speed can be decrease the brake torque. The conversion of direct injection diesel engine to multi point injection dedicated CNG engine can reduce the engine brake torque performance.

The maximum brake torque of direct injection diesel engine convert to multi point injection dedicated CNG engine is reduced 13.84%. The increasing engine speed can be increase the deviation point or percentage of the brake torque of diesel engine compared to CNG engine. So, the increasing engine speed can be increase the percentage deviation of brake torque both of the CNG engine and diesel engine. If both of the engines are running on 1000, the conversion of engine reduced brake torque of 2%. On the 1500 rpm engine speed, the conversion of engine reduced brake torque of 10.83%. If both of the engines are running on 2000, the conversion of engine reduced brake torque of 14.89%. If the engines are running on 2500, the conversion of engine reduced brake torque of engine is 26.43%. If the engines are running on 3000, the conversion of engine reduced brake torque of engine is 47.65%. On 3500 rpm, the conversion of engine reduced brake torque of 59.86%. On 4000 rpm, the conversion of engine reduced brake torque of 70.98%.

CONCLUSION

The engine torque performance investigation results such as indicated torque, crank pin torque, friction torque, shaft torque and brake torque of the four stroke direct injection diesel engine converted to sequential or multi point injection dedicated CNG engine are shown that the engine conversion can be decrease the engine torque performance. The increasing of engine speed can be decrease the engine torque performance. The highest of engine torque is declared in medium engine speed and the lowest is declared in high engine speed. The increasing engine speed will be increase the percentage deviation of CNG engine compared to diesel engine. The lower engine torque of CNG engine compared to diesel engine is caused by the lower of hydrocarbon, energy and higher friction of CNG as fuel.

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