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Predicting the Performance and Emissions Characteristics of a Medium Duty Engine Retrofitted with Compressed Natural Gas System using 1-Dimensional Software

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Abstract. The rise of crude oil price and the implications of exhaust emissions to the environment from combustion application call for a new reliable alternative fuel. A potential alternative fuel for compression ignition (C.I.) engine is the compressed natural gas (CNG). For C.I. engines to operate using CNG, or to be converted as a retrofitted CNG engine, further modifications are required. Previous works reported loss in brake power (BP) and increase in hydrocarbon (HC) emission for C.I. engine retrofitted with CNG fuelling. Verification of performance characteristics for CNG retrofitted engine through experimental analysis requires high cost and is very time consuming. Thus, a 1-Dimensional simulation software, GT-Power, was introduced in this study to reduce the experimental process and setup. A 4-cylinder medium duty C.I. engine (DE) and CNG retrofitted engine (RE) GT-Power models were used in this simulation work over various operational conditions: low, medium and high load conditions. As compared with DE model, results from RE model showed that RE model achieved an average 4.9% improvement for brake specific fuel consumption (BSFC) and loss in BP by 37.3%. For nitrogen oxides (NO_X) and carbon dioxides (CO_2) RE model predicted reduction of 48.1% (engine mode 1-9) and 33.4% (all engine modes), respectively. Moreover, RE produced 72.4% more carbon monoxide (CO) and 90.3% more HC emission.

Introduction

In 1997 an international summit was held at Kyoto, Japan to discuss on environmental issues. The main card is to stabilize the atmospheric concentration of Greenhouse gases (GHG) which causes global warming. One of the main factors is the combustion of hydrocarbon from crude oil [1]. The current emission pollution has focused the world attention to develop alternative fuel and reduce dependency on fossil fuel. An approach has been made which seen the usage of natural gas appears to be a suitable candidate in order to overcome the emissions problem caused by internal combustion engine fuelled with diesel.

Natural gas, is a fossil fuel primarily consisting of methane and is one of the cleanest burning alternative fuel. It can be used in the form of compressed natural gas (CNG) and liquefied natural gas (LNG) to fuel automobile vehicles. The interesting part of natural gas is, when it burned it gives high amount of energy with lower emission to the environment. According to Cascetta et al. [2] The use of natural gas as a vehicle fuel has some advantages: (1) it has high octane number, (2) it produces clean burning, and (3) it produces low CO_2 unit of energy than other fossil fuels.

CNG is used traditionally in spark ignition engine converted into bi-fuel vehicles. In order to implement CNG to diesel engine require added components as well as some mechanical changes to the engine. Basically the diesel engine undergoes complete changes on compression ratio, injection type, and modification of cylinder head for spark plug. Through 1-dimensional simulation software GT-Power, the conversion process was done based on the engine layout and the geometry measured by the actual basic engine condition.

Effects of CNG on engine performance and emission

The current state of natural gas vehicle (NGV) is based from conversion of spark ignition and compressed ignition engines where they are operated in mono-gas, bi-fuel or dual fuel mode. Each conversion undergoes different type of modification, this reflected to the engine performance and exhaust emissions characteristics of the engine. With careful modification the lower output of brake power can be overcome by using high compression ratio, raise in valve lift, effective valve timing and decrease in backpressure engine [3]. In retrofitted spark ignition engine NO_x is still the main fear due to the elevated production of exhaust gas temperature. However, retrofitted spark ignition is still low in CO, CO_2, HC, etc and better fuel consumption with superior brake thermal efficiency compared to gasoline [4]. A new method to reduce NO_x emission is through modification of fuel injection system by direct injection. By comparison the performance of CNG in direct injection (CNG-DI) can produce higher performance than CNG-Bi fuel system and is on a par with multi cylinder gasoline port injection (PI) engine. In the overall exhaust emission, CNG-DI is cleaner than gasoline-PI and CNG-Bi but still high in CO emission due to the leaner combustion [5]. For modification of diesel to CNG engine must at least involve using lower compression ratio, and substituting all the injector with the addition of spark plug, thus the diesel engine is converted to a spark ignition engine [6]. Converted compression ignition engine to natural gas direct injection produces high NOx at higher compression ratio and increased in HC at high load condition [7]. Combination of diesel and natural gas or namely a dual fuel mode experiences drop in brake thermal efficiency but can be improved by implementing exhaust gas recirculation [8].

Computational engine modeling

Over the last decade, the development of computational engine simulation modeling had expanded widely, in order to mimic the real condition of the experimental testing. In fact the simulation can offer a reliable prediction on the effect of modification to the engine geometry, hence it gives benefits as less time is required in preparing a test bed due to fast analysis. GT-Power is introduced in this study to dynamically simulate the engine performance and emission for DE and RE because of fast computational speed and has been commonly used in automotive industry.

Engine modeling setup

Elementary feature in modeling 1-dimensional GT-Power software are the component from flow and mechanical library. The detail of the basic engine system that was used in the engine crank train is based on Table 1. Fig. 1 shows how the components are linked based on GT-Power engine mapping computational model. In order to convert the DE to a RE, modifications of the design in engine system are required. Since RE used a throttle body injection, the DE fuel injection system was replaced from Injprofile connection to InjAF-RatioConn which inflict air-fuel ratio. Stochiometric air-fuel ratio used in this analysis is 14.3 and 17.3 for DE and RE respectively [9]. Different fuel type used in this study necessitates a different combustion process. EngCylCombDI-Wiebe (compression ignition) and EngCylCombSI-Wiebe (spark ignition) combustion was used in Engcylinder to couple with Injprofile connection and InjAF-RatioConn respectively. Table 2 shows the case setup to study the effects on various engine performance and emission at different engine load. The case was setup; low, medium and high load; at different engine speed [10].

Table 1: Engine parameters

	Diesel Engine	Retrofit Engine
Engine Type	4 stroke	
Number of Cylinders	4	
Combustion System	Direct Injection	Throttle Body Injection
Bore x Stroke (mm)	112 x 110	
Compression Ratio	19:1	11:1
Connecting Rod Length (mm)	165	
Fuel Type	Diesel	CNG

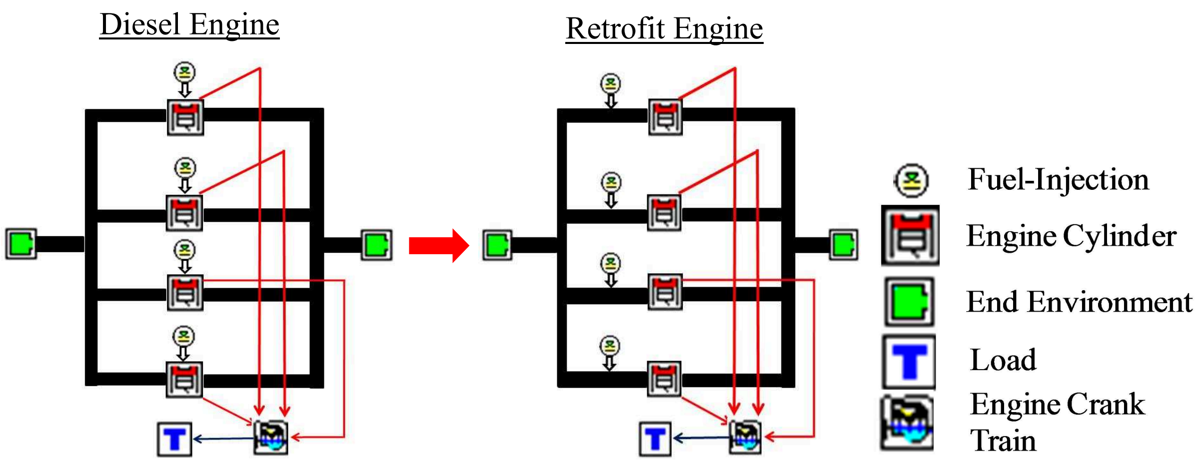

Fig. 1: GT-Power engine mapping computational model

Table 2: GT-Power case setup

Engine mode	1	2	3	4	5	6	7	8	9	10
Engine Condition		Low load			Medium load				High load	
Engine speed (RPM)	1000	2000	3200	1300	2400	1500	2100	2100	2600	3000
Load (Nm)	16.3	17.6	17.6	58.3	36.6	96.3	70.5	122	135.6	175

Result and discussion

Fig. 2(a) presents the BP at all engine modes condition. The graph show that BP is low at all operating modes. The main reason of the reduction of BP for RE is longer ignition delay and lower CNG flame speed. The highest BP achieved by RE is 41.7kW at high load with engine speed 2600 RPM at 135.6 Nm meanwhile DE shows maximum value of 82.3 kW with engine speed 3000 RPM at 175 Nm. A close gap occurs at low load condtion, however as the engine load raise the percentage difference increases with average at all operating condition 37.3% compared to DE.

Fig. 2(b) shows the variation of BSFC at engine mode condition. In all operating condition RE had always been lower than DE throughout all the engine modes. This was mainly due to the higher heating value of CNG (48 MJ/kg) compared to diesel fuel (45 MJ/kg). Average of BSFC recorded at all engine modes is 4.9% less than DE which shows that RE is very effective at low engine load with percentage of difference below 7.04%.

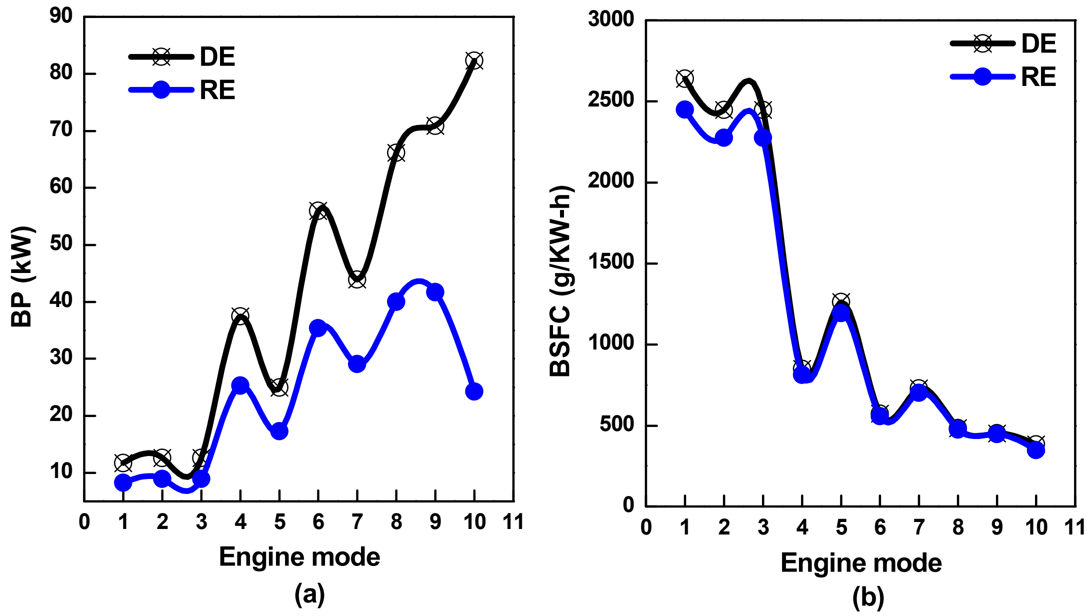

Fig. 2: BP and BSFC at engine mode condition

Fig. 3(a) indicates the NO_x concentration at engine mode condition. Based on the result RE shows the maximum NO_x emission at high load with 2117.7 PPM followed by DE 1909.8 PPM at engine mode 10. Interestingly, engine mode 1-9 RE able to reduce NO_x emission on average of 48.1% as compared to DE. Generally the reason for this phenomena is the cool gaseous flowing into engine cylinder thus the combustion accomplished at low engine temperature [5].

Fig. 3(b) denotes the HC concentration at engine mode condition. From the result RE shows a high HC emission with an average percentage of differences by 90.3% compared to DE at all engine mode condition. RE produces superior HC due to the imperfect combustion of the hydrocarbon fuel. Emissions from HC generated from CNG fuel mostly methane (CH_4) does not bring too much harmful compared to liquid fuels [11].

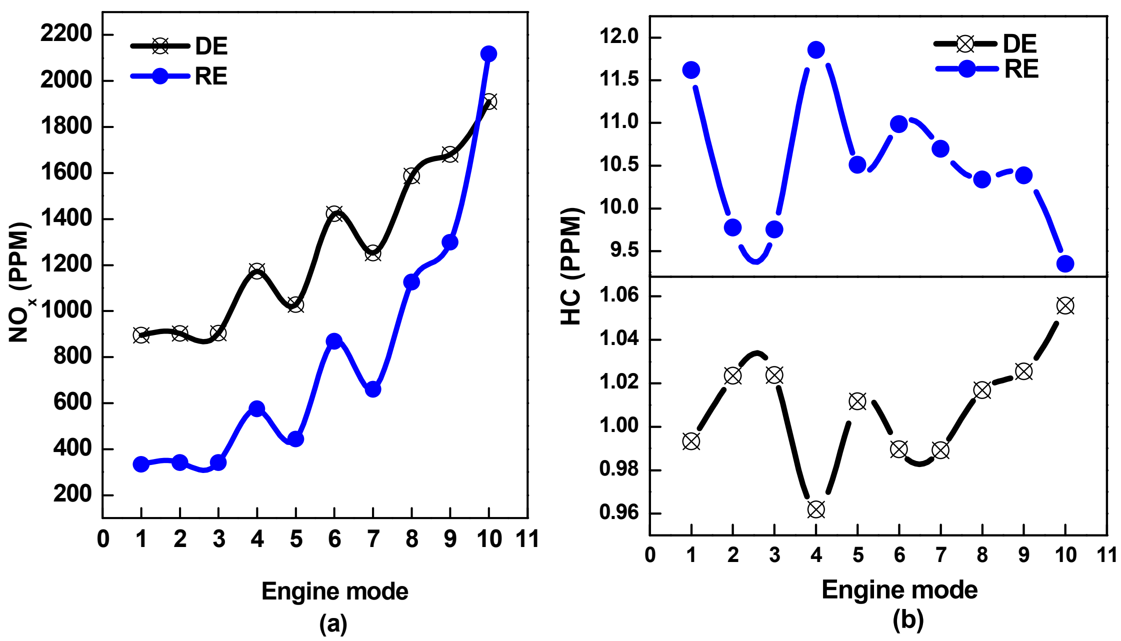

Fig. 3: NO_x and HC emissions at engine mode condition

Fig. 4(a) shows the result for CO emissions at engine mode condition. Based on the following graph the lowest concentration of CO was produced from DE by an average of 818.6 PPM followed by RE with 2989.6 PPM. Between engine mode 9 and 10 show that CO concentration decrease by 27.4% suggesting that combustion efficiency increase at high load condtition. RE emit higher CO concentration due to the limited oxygen to convert to CO_2.

Fig. 4(b) demonstrates CO_2 emissions at engine mode condition. Maximum CO_2 recorded at engine mode 10 which is 136874 and 91825.6 PPM for DE and RE respectively. Throughout the graph, RE experienced a lower CO_2 emissions compared to DE with percentage of reduction below 33.4%. Theoretically the reason of lower CO_2 emissions was due to the lower hydrogen to carbon ratio of CNG compared to diesel fuel [11].

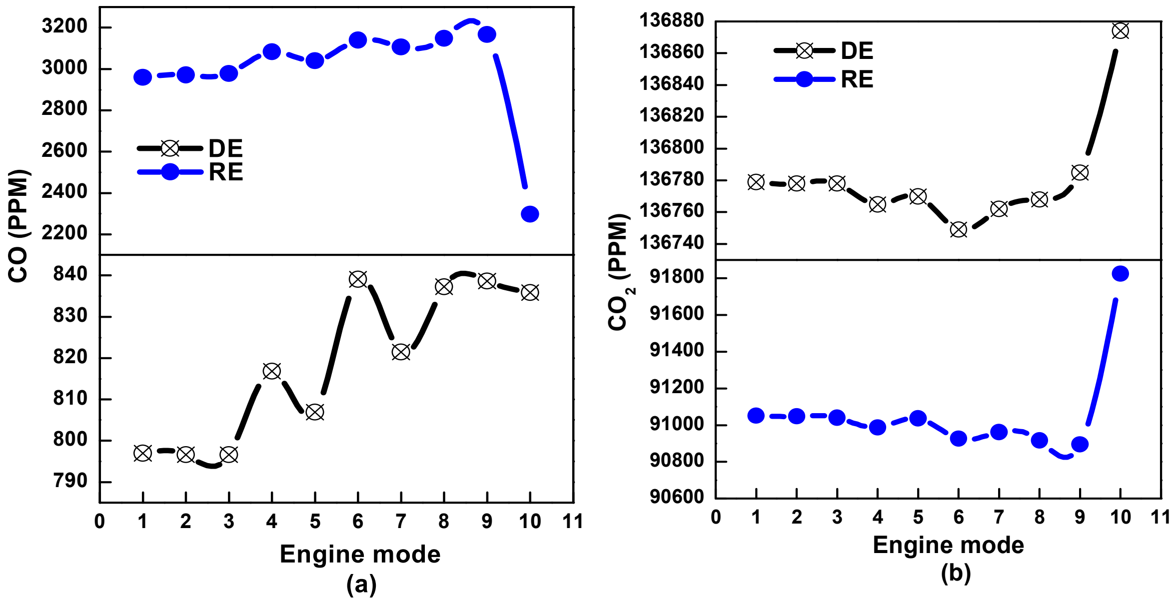

Fig. 4: CO and CO_2 emissions at engine mode condition

Conclusion

In this study the effect of conversion from DE to RE involving compression ratio, fuel injection system and fuel type has been predicted by using 1-dimensional simulation software GT-Power. The developed model is tested at various engine performance and emissions. Based on the investigation RE show that CNG is a better fuel choice economically and environmentally. The result can be summarized below:

(i) RE produces lower BP at all engine modes with an average reduction of 37.3% as compared to DE.
(ii) A reduction of 4.9% for BSFC achieved by RE compared to DE.
(iii) Decreased of NO_x exhaust emissions with percentage of difference 48.1% from engine mode 1 – 9 compared to DE.
(iv) High HC emissions contributed by RE at all engine modes condition with an average of 90.3%. compared to DE
(v) RE leads the highest CO emissions by percentage of difference at all engine modes condition with 72.4% compared to DE.
(vi) DE shows superior CO_2 emissions with 33.4% at all engine modes compared to RE.

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