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COMPUTATIONAL SIMULATION AND EXPERIMENTAL VALIDATION OF A TURBOCHARGED DIESEL ENGINE

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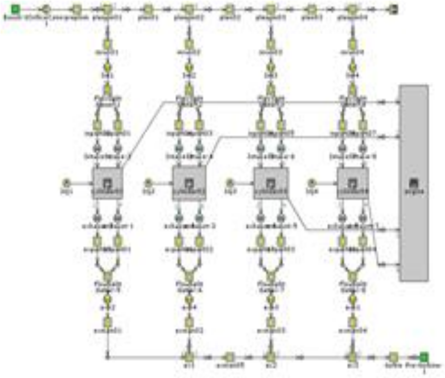
Graphical abstract



Abstract

Requirements for sustainable development and green technology are motivating car manufacturers to produce newer efficient engines with more power and reduce hazardous emissions. The development of modern engines has certain constraints since prototyping phase requires longer time and is costly. Engine computational modelling now becomes a useful approach and can be used as a predictive tool when developing new engine concepts. The aim of this work is to develop and experimentally validate a turbocharged diesel engine model using one-dimensional GT-Power software. The engine performance parameters in terms of power and torque which are dependent to engine speed are being presented. The predicted performance parameter of the engine model is compared with the data obtained during engine dynamometer experiments. The simulation results show that the engine performances such as engine power and torque are in good agreement with the experiment results within the engine rpm range from 2000 rpm to 3000 rpm (with RMS Error for engine power and torque is 10% and 39%).

Keywords: Diesel engine; GT-Power

Abstrak

Keperluan untuk mengekalkan pembangunan yang mampan dan teknologi hijau, menjadi motivasi kepada pengeluar kenderaan untuk menghasilkan enjin yang lebih cekap serta mampu menghasilkan lebih banyak kuasa dan mengurangkan pelepasan gas-gas berbahaya. Pembangunan enjin yang terkini mempunyai kekangan tertentu seperti fasa prototaip yang memerlukan masa yang lama untuk dibangunkan serta mahal. Pemodelan pengkomputeran enjin kini menjadi pendekatan yang lebih baik dan boleh digunakan sebagai alat ramalan semasa membangunkan konsep enjin baru. Tujuan kajian ini adalah untuk membangunkan model enjin diesel berpengecas turbo menggunakan perisian pengkomputeran satu-dimensi GT-Power dan mengesahkan model tersebut melalui ujikaji. Parameter prestasi enjin seperti kuasa dan daya kilas yang bergantung kepada kelajuan enjin akan dibentangkan. Parameter prestasi ramalan model akan dibandingkan dengan data yang diperolehi semasa ujikaji enjin yang menggunakan dinamometer. Keputusan simulasi menunjukkan bahawa prestasi enjin seperti kuasa enjin dan penghasilan daya kilas hampir bersamaan dengan hasil ujikaji dalam julat rpm enjin dari 2000 rpm kepada 3000 rpm (dengan ralat RMS untuk kuasa enjin and daya kilas adalah 10% dan 39%).

Kata kunci: Enjin diesel; GT-Power

1.0 INTRODUCTION

In recent years, engine simulation tools such as GT-Power, Boost, Lotus and etc. has been used widely for engine development. It can offer fast and accurate combustion models, emission simulation models [1] and more importantly it can minimise the requirement of costly test-bed measurements. It allows the modelling for individual parts of a process independently, which leads to a better understanding of the process as a whole. This would reveal areas where there exist potentials for future development. Several good example of engine simulations can be found in [2], [3] and [4].

To obtain an accurate prediction of the engine behaviour, an analysis of a turbocharged diesel engine conducted through a high-fidelity gas dynamic simulation code calibrated on experimental data need to be carried out [5]. In this work, the turbocharger parameters such as inlet pressure, outlet pressure and temperatures were obtained from the experimental works. These values were imposed into the GT-Power simulation, in order to generate engine performance (power and torque). This approach is essential due to lack of turbocharger specification from manufacturers. The experiments were carried out initially to focus on the engine performance measurement where the comparison between simulations and the experimental engine performance parameters such as power, torque and brake specific fuel consumption (BSFC) is discussed.

2.0 MODEL SETUP

Generally, a one-dimensional (1-D) simulation of an engine model consists of intake system, exhaust system, fuel injection systems, engine cylinders and valve train. The developments of a one-dimensional model for a four-cylinder, four-stroke, direct injection Diesel engine is presented in this section. Figure 1 shows the diesel engine modelling using GT-Power software. This model represents a four-cylinder inline diesel Mitsubishi engine which is used for the experimental works with its specification given in Table 1.

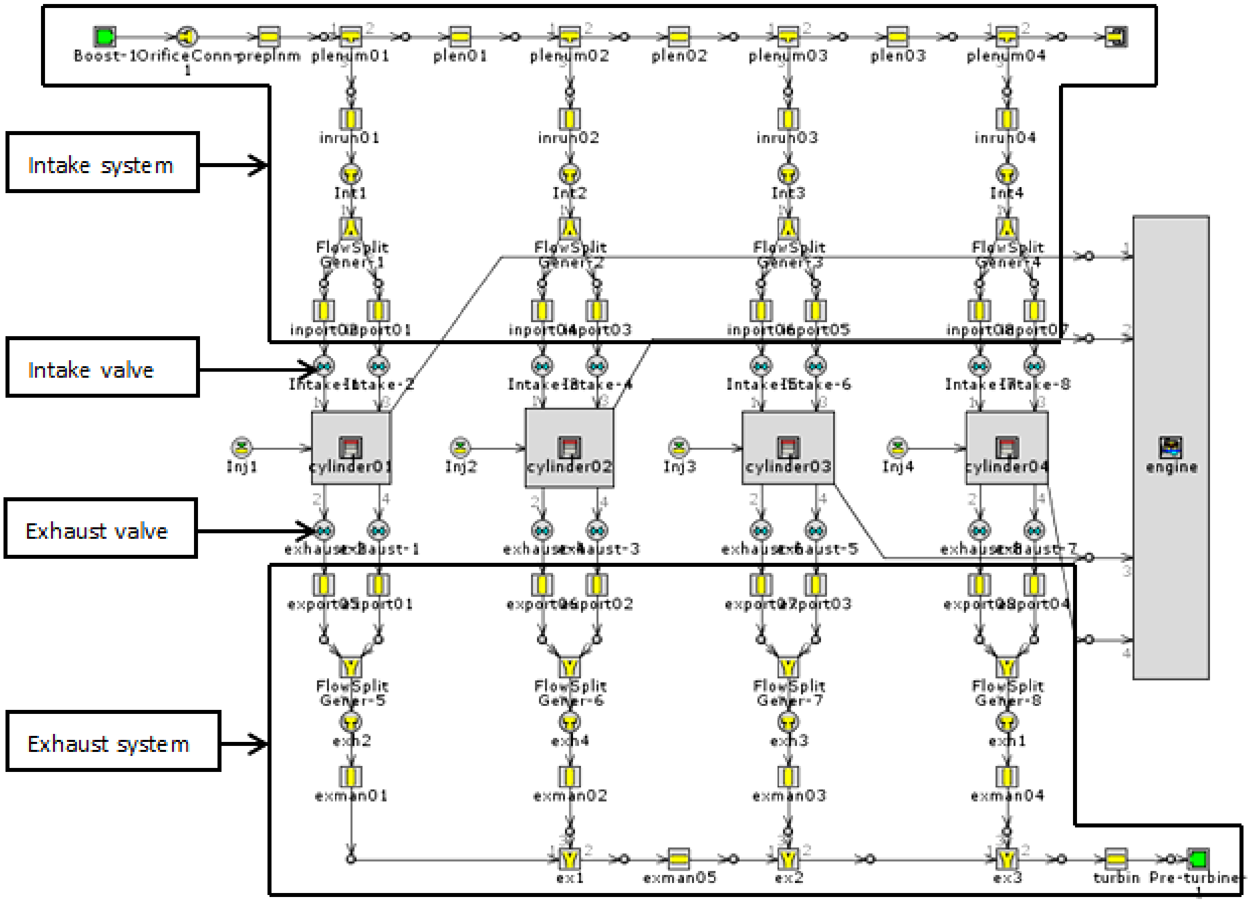


Figure 1 GT-Power model for the four-cylinder turbocharged diesel engine

Table 1 Engine parameter specification

Parameter	Technical Specification
Type	4-cylinder Turbocharged Direct Injection
Bore (mm)	98.5
Stroke (mm)	105
Compression ratio	17
Displacement (cc)	3200
Connecting Rod Length (mm)	152
Injection Timing	4^0 BTDC
Number of Intake Valve	8
Number of Exhaust Valve	8

Initial step on building engine model in GT-Power is to model the intake system. For the selected diesel engine, the intake system has a few components such as *boost environment* (inlet condition), *plenum* (intake manifold), *inrun* (intake runner), and *inport* (intake port). These components represent the pipes with specific parameters as shown in Table 2. Developing a turbocharger model in GT-Power requires detail manufacturer specifications such as compressor map, turbine map and shaft moment of inertia, which was not made available and mostly are confidential in nature. Hence, the *boost environment* attributes such pressure and temperature was obtained using data from the experimental result. The *intake* (intake valve) specifications as shown in Table 3.

Table 2 Parameters for intake system

	plenum	***inrun***	***inport***
Diameter at inlet end (mm)	80	47	47
Diameter at outlet end (mm)	80	47	47
Length (mm)	51	100	95
Discretization length (mm)	50	50	50
Initial state name	Boost		

Table 3 Parameters for intake and exhaust valve

	intake	***exhaust***
Valve reference diameter (mm)	33	31
Valve lash (mm)	0.35	0.4
Cam timing angle ^{0}CA	231	126

In this simulation, combustion is modelled by *EngCylCombDIPulse* [7] and heat transfer is modeled by *WoschniGT* [7]. This combustion model predicts the combustion rate and associated emissions for direct-injection diesel engines with single and multi-pulse injection events. While the in-cylinder heat transfer will be calculated by a formula which closely emulates the classical Woschni correlation without swirl [7].

In the engine crank train, various attributes such as number of cylinders, configuration of cylinder and engine type need to be defined. The dimensions of components in the engine cylinder geometry such as bore, stroke, connecting rod, wrist pin to crank offset, compression ratio, TDC (top dead centre) clearance height and connecting rod length are measured corresponding to the exact engine specifications.

The exhaust system has a few components such as *pre-turbine environment* (outlet condition), *exman* (exhaust manifold) and *export* (exhaust port). These components represent the pipes with specific parameters as shown in Table 4. The *pre-turbine environment* attributes such as pressure and temperature were imposed from the experimental data as well. The *exhaust* (exhaust valve) specifications as shown again in Table 3.

Table 4 Parameters for exhaust system

	exman	***export***
Diameter at inlet end (mm)	47	47
Diameter at outlet end (mm)	47	47
Length (mm)	100	95
Discretization length (mm)	50	50
Initial state name	Pre-turbine	

3.0 EXPERIMENTAL SETUP

The experiment was performed on an engine dynamometer test bed as shown in Figure 2. The engine performance was measured using an eddy-current dynamometer that was dedicated to control engine torque or speed. This activity follows SAE standard, (SAE J1349) [6], ensuring strict compliance to obtain the performance measurement. The atmospheric conditions (Table 5) and diesel fuel specifications (Table 6) during the testing were adhered to and controlled so as to be within the limit stated by the SAE standard. The tested fuel parameters such as fuel density and fuel kinematic viscosity are based on diesel specification as stated by [8].

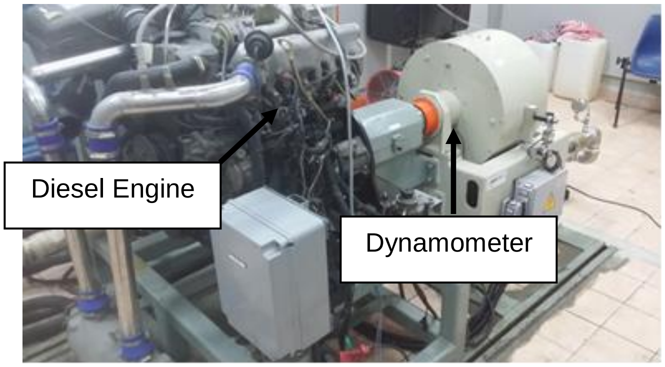


Figure 2 Four-cylinder turbocharged diesel engine on dynamometer

Table 5 SAE Reference Atmospheric Conditions [6]

	Standard Condition	**Test Range Limits**	**Test Conditions**
Inlet Air Supply Pressure (absolute)	100 kPa	-none-	100 kPa
Dry Air Pressure (absolute)	99 kPa	90-105 kPa	101 kPa
Inlet Air Supply Temperature	25 °C	15-35 °C	34-35 °C

Table 6 SAE Reference CI Fuel Specifications [6]

	Standard Condition	**Test Range Limits**	**Test Conditions**
Fuel Density at 15 °C	0.850 kg/L	0.840 - 0.860 kg/L	0.810 – 0.870 kg/L [8]
Fuel Kinematic Viscosity at 40 °C	2.6 mm²/s	2.0 - 3.2 mm²/s	1.6 – 5.8 mm²/s [8]
Fuel Inlet Temperature	40 °C	39 - 41 °C (pump/line/nozzles/common rail)	33 °C
		37 - 43 °C (unit injectors)	--

4.0 RESULTS AND DISCUSSION

The comparison of the engine power from simulation and experimental results were presented within the range of 1500 rpm to 4000 rpm. The low speed measurement of around 1000 rpm could not be conducted due to a technical limitation of the test bed. The engine power resulted from the simulation and experiments were plotted against engine speed (rpm) as shown in Figure 3. Preliminary result shows that the simulation curve trend is in good agreement with the experimental result. A close resemblance occurred from 2000 rpm to 3000 rpm representing small discrepancy in simulation model. It can be seen that the maximum power achieved at 3500 rpm for both results. The maximum power for simulation and experiment were recorded at 118.5 kW and 106.9 kW respectively. The Root Mean Square Error (RMSE) of engine power between the simulation and experiment was 10% for the entire range of rpm. The maximum percentage error of 22% occurred at 1500 rpm and minimum percentage error of 1% occurred at 2500 rpm as shown in Table 7.

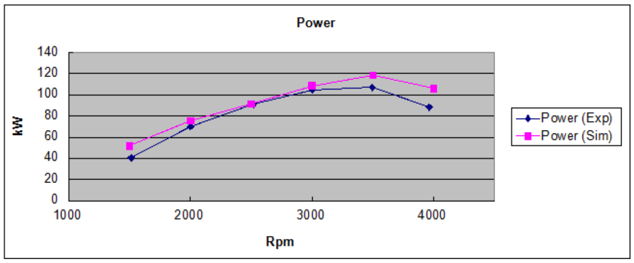


Figure 3 Comparison between measured and simulated of engine power

Table 7 Root Mean Square Error (RMSE) between simulation and experiment for power (kW)

Power (kW)				
RPM	Simulation	Experiment	% of error	RMS Error
1500	51.8	40.5	22	10
2000	75.5	70.2	7	
2500	91.6	91	1	
3000	108.6	104.4	4	
3500	118.5	106.9	10	
4000	106.2	88.3	17	

Similarly, the engine torque resulted from the simulation and experiments were plotted against engine speed (rpm) as shown in Figure 4. It is found that the simulation curve matches closely with the experimental result. A close prediction is achieved from 2000 rpm to 3000 rpm representing small discrepancy in the simulation model. It can be seen that the maximum torque for simulation model occurred at 2000 rpm and for the experiment at 2500 rpm. The maximum torque for simulation and experiment are 360.3 Nm at 2000 rpm and 344.9 Nm at 2500 rpm respectively. The Root Mean Square Error (RMSE) of engine torque between the simulation and experiment was 39% for the entire range of rpm. The maximum percentage error of 23% occurred at 1500 rpm and minimum percentage error of 1% occurred at 2500 rpm as shown in Table 8.

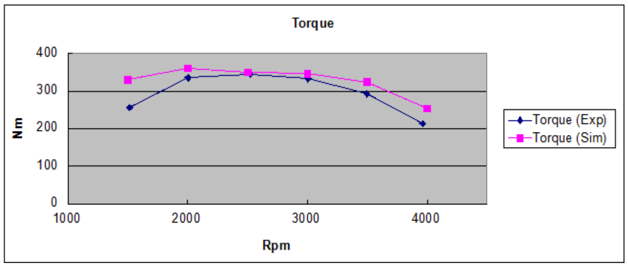


Figure 4 Comparison between measured and simulated of engine torque

Table 8 Root Mean Square Error (RMSE) between simulation and experiment for torque (Nm)

Torque (Nm)				
RPM	Simulation	Experiment	% of error	RMS Error
1500	329.9	255.5	23	39
2000	360.3	334.9	7	
2500	349.9	344.9	1	
3000	345.8	332.2	4	
3500	323.4	292.1	10	
4000	253.5	212.9	16	

Figure 5 shows the comparison of simulation and experiment of brake specific fuel consumption (BSFC) against engine speed (rpm). The result shown was also measured from 1500 rpm to 4000 rpm. Preliminary result shows that the simulation curve trend is in agreement with the experimental result.

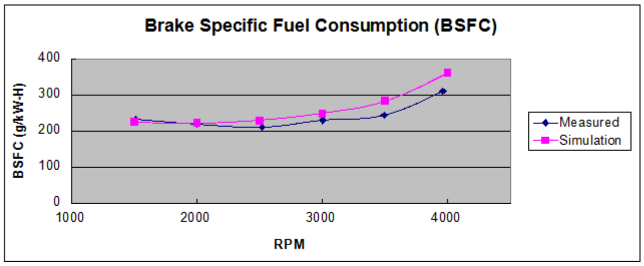


Figure 5 Comparison between measured and simulated of engine Brake Specific Fuel Consumption (BSFC)

A close resemblance occurred from 1500 rpm to 2000 rpm representing small discrepancy in simulation model. The Root Mean Square Error (RMSE) between the simulation and experiment for Brake Specific Fuel Consumption (BSFC) was 29% for the entire range of rpm. The maximum percentage error of 14% occurred between 3500 rpm to 4000 rpm and minimum percentage error of 1% occurred at 2000 rpm as shown in Table 9.

Table 9 Root Mean Square Error (RMSE) between simulation and experiment for Brake Specific Fuel Consumption (BSFC)

BSFC				
Engine Speed RPM	Simulation SFC g/KWH	Measured SFC g/KWH	% of error	RMS Error
1500	225.8	233.3	-3	29
2000	222.6	220.1	1	
2500	229.3	211.3	8	
3000	248.5	228.7	8	
3500	283.5	243.9	14	
4000	361.7	310.3	14	

5.0 CONCLUSION

Comparisons of the engine performance parameters such as power, torque and brake specific fuel consumption have been validated from the results of experiment and simulation data. From the results, it shows that all engine performance trend curves are considerable to be in good agreement between the simulation and experimental results. The study was done with consideration that the GT-Power simulation used the pressure and temperature data obtained from experimental result to substitute the turbocharger model. A detailed turbocharger modeling which may provide closer to real-time data would help to develop a better accuracy in the above activity.

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