1-D ENGINE MODELING OF 4-CYLINDER TURBOCHARGED GASOLINE ENGINE

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ABSTRACT

This project is conducted to explore one-dimensional (1D) simulation for a 4-cylinder gasoline engine. The simulation and computational development of modeling for the study are conducted by using the commercial Computational Fluid Dynamics (CFD) of AVL BOOST software. The engine model was developed corresponding to a Proton 1.6-litre CamPro 4-cylinder turbocharged gasoline engine including the real engine geometry and parameters. The engine model is based on 1D equation of the gas exchange process, progressive engine combustion process, isentropic compression and expansion, and accounting for the heat transfer as well as the frictional losses. The aim of the study is to predict the steady-state performance of the engine model at full and part- load conditions from 1000 to 5000 rpm by using engine cycle simulation. In this study, three parameter tuning works have been performed, which are combustion model tuning, intake manifold temperature tuning and turbocharger's scaling factor tuning. In addition, the comparison and validation were done for the output performance parameters based on the provided experimental data. Overall, the engine performance behavior has been observed to determine how accurate AVL BOOST software can evaluate engine performance compare to experiment conducted on the real engine. The most accurate validation of the engine performance parameters has been achieved by manifold absolute pressure (MAP) with 3.14% error. However, by comparing with experimental data, major discrepancy is noticeable on several engine performance parameters. From this study, the results showed that the engine model is able to simulate engine's combustion process and produce reasonable prediction.

KEYWORDS

One-Dimensional, Gasoline, Simulation, AVL BOOST, Validation

1.0 INTRODUCTION

In this new era, there are many automotive manufacturers competing among themselves todevelop internal combustion engines (ICEs) while simultaneously reducing pollutant emissions by using computer simulation. Computer simulation is able to provide good estimates of performance changes resulting from possible engine modifications and thus can help in reducing the amount of hardware development required. Nowadays, there are several available engine simulation commercial software packages used in the automotiveindustry such as GT-POWER, Lotus Engine Simulation (LESoft), Ricardo WAVE and AVL BOOST (Chan et al., 2013) [1]. For the purpose of this project, AVL BOOST has been used for the 1D engine modeling and simulation.

AVL BOOST is a fully integrated ICE simulation software which can simulate an entireICE including all the parts of the engine and also be coupled with external software programs or third-party tools to study specific parts (AVL List GmbH) [2]. Ling [3] stated that it is a 1D engine simulation software which can simulate a wide variety of engines with different type of ignition systems including compression ignition (CI) and spark ignition (SI). It can basically solve any engine configuration by performing thermodynamics and internal flow analysis throughout the simulation. Moreover, Alqahtani [4] described that it is a high simulation program, with quite accurate results and reliable.

In addition, the calculation model can better anticipate the engine performance, examine different parameters in a brief time frame and provides guidance for improving engine performance (Wei et al., 2013) [5]. For this project, the 1D Computational Fluid Dynamics (CFD) theory have been implemented to model the 1D engine simulation by using AVL BOOST software. In addition, the AVL BOOST is able to predict steady-state or transient engine operation and the output results could be time resolved, crank-angle or single value quantities. The basic layout of the engine model used for the simulation is a 4-cylinder, 1.6- litre, turbocharged, multi-port fuel injection gasoline engine which is readily available in the software template library as an example base engine. The simulation is carried out to predict steady-state engine performance characteristics such as the manifold absolute pressure (MAP), intake manifold temperature, mass air flow, pertinent turbocharger parameters and etcetera. Furthermore, the engine performance parameters were validated with the provided experimental data.

Based on literature, many previous studies on 1D CFD engine simulation come out with different error band for the major engine parameters. For example, Cordon et al. [6] mentioned that an engine model can be utilized with an elevated level of certainty to optimize engine parameters if the model can be validated to high degree of accuracy such as 5%. Bayas et al. [7] have reviewed about a research work done by Jensen Samuel et al, in their dissertation. Jensen Samuel et al, conducted simulations on a 1000hp V46-6 turbo diesel engine and validated major engine parameters to study the effect of variable length intake manifold on a turbocharged multi-cylinder diesel engine. From the validation, the deviations were found to be less than 5% of the experimental data. In another study, Cieslar, D. [8] has validated a 2-litre diesel engine supplied by Ford Motor Co in his research work entitled "Control for Transient Response of Turbocharged Engines". It is observed that the deviations were found to be within a 10% band. Overall, it can be concluded that the acceptable deviation should be within 10% error band. It is important to comply the acceptable deviation in order to evaluate the ability of the engine model to represent real engine behavior.

2.0 METHODOLOGY

AVL BOOST™ v2016 was used as the 1D simulation software throughout this study. It has been employed to predict the steady-state engine performance. There are 2 software domains provided by the AVL BOOST which are AWS GUI and IMPRESS CHART as shown in Figure 1 below. Hence the detail function of these software domains has been applied in this study.

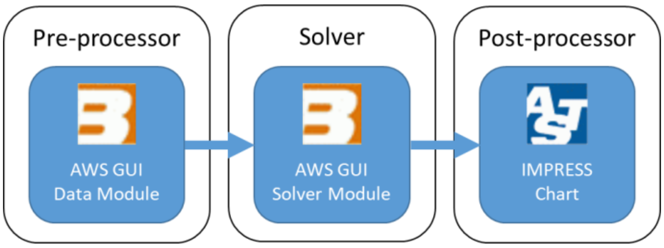


Figure 1: Three primary processor tool in AVL BOOST employed in this project

All the methodology work flow is being presented by the flow chart below. First of all, a thermodynamic model for the four cylinder turbocharged gasoline engine was created in AVL BOOST software using various elements and suitable models. Various suitable models for combustion, heat transfer, friction etc. were selected for the engine model. Thevalues for the design and operating parameters of the engine were given as input to the model. Figure 3 below shows the schematic model of the Proton CamPro engine and the description of the variables are as follow. Firstly, E1 represents the engine while C1 to C4are the cylinders of the engine. MP1 to MP17 symbolize the measuring points. The plenumis market with PL1. SB1 and SB2 are for the system boundary. The flow pipes are numbered 1 to 43. TH1 and TH2 represent the throttle and CL1 represents the cleaner. R1and R2 represent flow restrictions, CO1 represents air cooler and I1 to I4 stand for fuel injectors. Lastly, TC1 symbolizes the turbocharger.

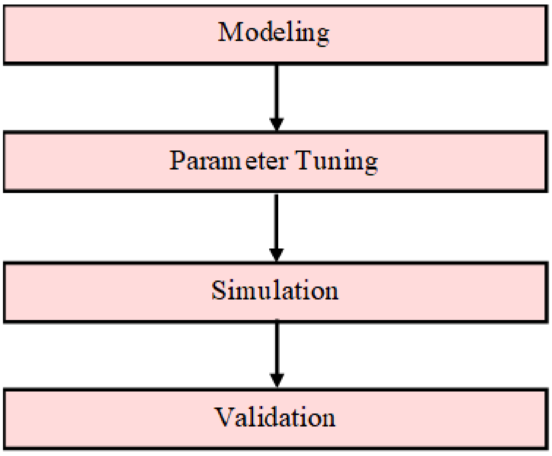


Figure 2: Flow chart of the project methodology

As previously noted, the complete engine model was designed by various element which represent the mechanistic components in an ICE. Although the models are based on mechanistic models, they incorporate many tuning parameters needed to be adjusted to setup the high fidelity ICE simulation models. Therefore, some parameters tuning and validation works as shown in Figure 4, have been done through this project. The tuning processes were conducted mainly using simulation with fixed engine geometry and different engine operating parameters. The computations using engine cycle simulations were carried out under speed range of 1000 to 5000 rpm at 2 variable load conditions. Theyare full and part-load condition with corresponding to the percentage of throttle opening, 100% and 25%, respectively. The first tuning is focused on the optimization of combustionmodel parameters. For the intake manifold temperature tuning, the output performance parameter has been validated with the provided experimental data. Moreover, the turbocharger's scaling factor tuning have been performed for the parametric study of this project.

The results were generated for the performance validation of manifold absolute pressure(MAP), intake manifold temperature, turbine inlet pressure, turbine inlet temperature, massair flow and fuel flow rate produced by the modeled engine. The comparison of the resultswas done to evaluate the ability of the Proton CamPro engine model in predicting the performance parameters as the experimental data.

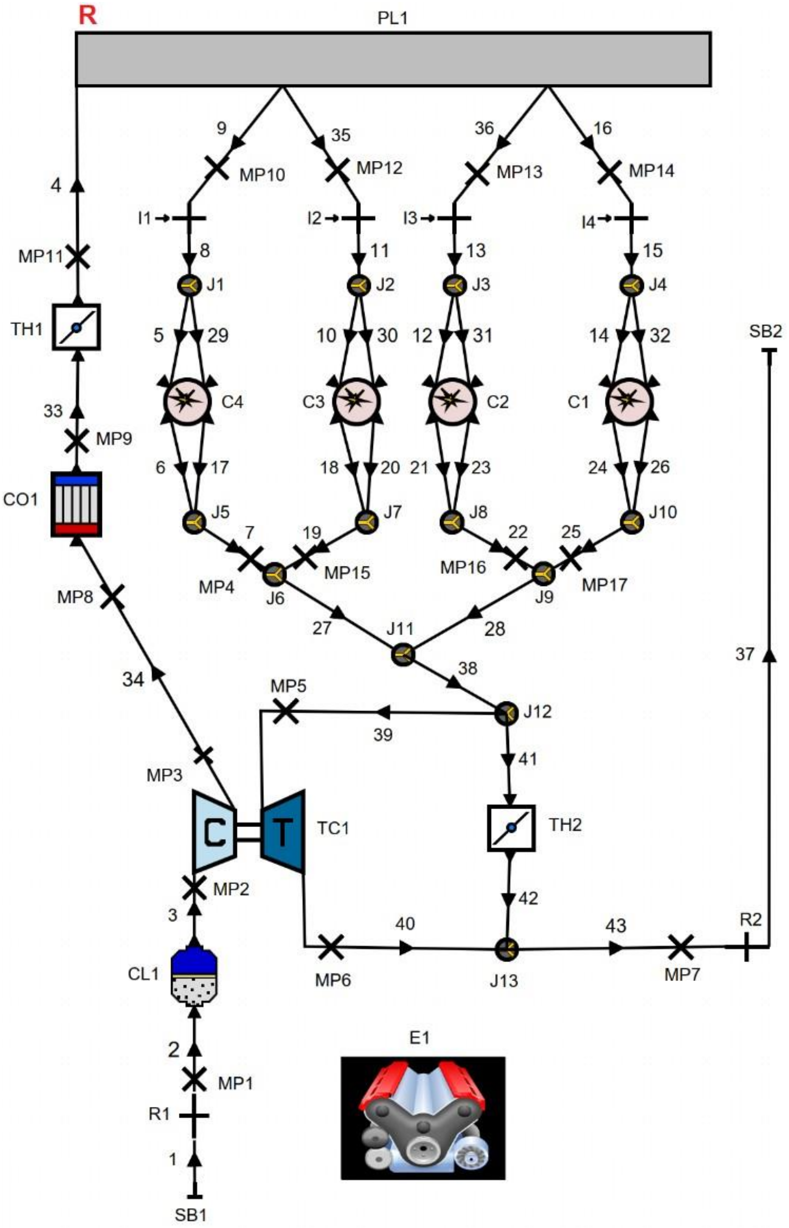


Figure 3: Schematic model of Proton CamPro engine model

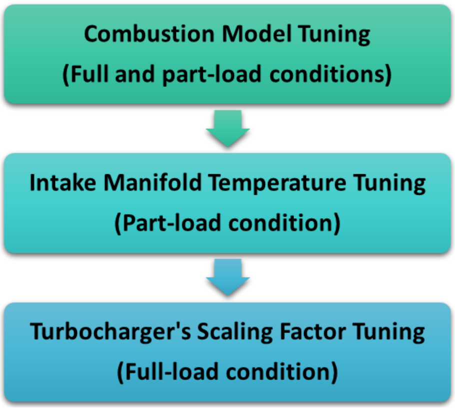
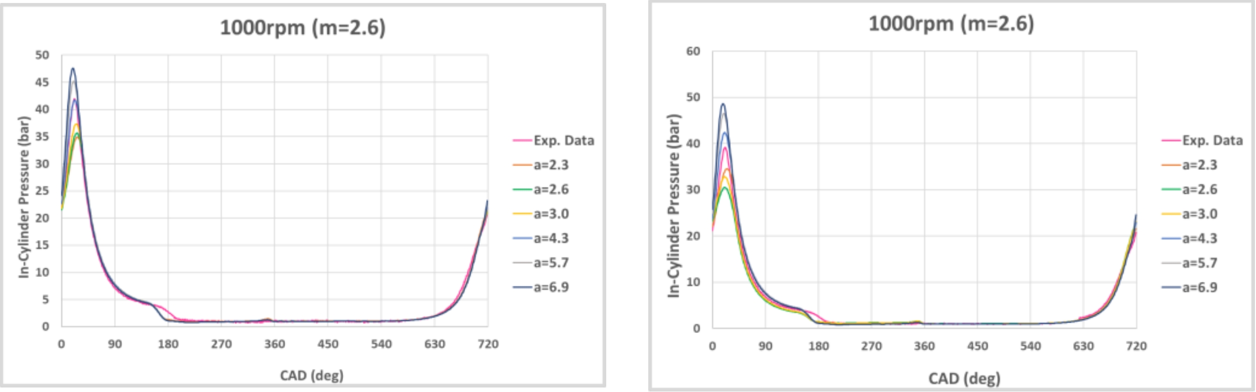


Figure 4: Flow chart of the engine model tuning process

3.0 RESULTS AND DISCUSSION

3.1 Analysis on Tuning of the Combustion Model with In-Cylinder Pressure Data at WOT and Part-load

The main findings for this tuning work concern the optimization of parameter ‘a’ for each operating point (speed) of the Proton CamPro engine model at full or wide open throttle (WOT) and part-load condition. It is one of the key parameters in defining the heat release characteristic of the combustion model, Vibe 2-Zone (J. B. Heywood., 1988) [9]. Basically, parameter ‘a’ characterizes the completeness of the combustion process with the theoretical range of 2.3-6.9 (AVL List GmbH) [1]. The prediction of parameter ‘a’ is done by comparing and interpolate the In-Cylinder Pressure from the simulation result with the experimental data. The objective of the tuning process is to evaluate the accuracy of the combustion model in predicting the Vibe parameter ‘a’ according to theory. For the result, the In-Cylinder Pressure data were extracted according to the operating points from the engine simulation and tabulated in graphs which have been pre-included with the experimental data in order to facilitate the comparison process. Figure 5 shows the sampleof variation In-Cylinder Pressure curves for WOT and part-load condition at 1000 rpm.



(a) (b)

Figure 5: In-Cylinder Pressure curves at, (a) WOT condition and; (b) part-load condition

The list of optimal value of parameter ‘a’ at each operating point is listed in Tables 1 and 2. There is no any performance parameter validation in this section. Based onthe result, it is found that only several operating points are complying the theoretical range in optimizing the value of parameter ‘a’. For the full-load condition, the acceptable parameter ‘a’ is only achieved at the idle speed which are 1000 and 1500 while for the part-load condition, it is achieved at 1000, 1500 and 2000 rpm. Overall, the value of parameter ‘a’ are not well-estimated because they have not met the theoretical range values of 2.3 to 6.9. This inadequate prediction result occurred in combustion model tuning is due to other several operating conditions in cylinder element which did not reach the optimum value during the simulations. For instance, in-cylinder wall temperature, heat release characteristic and etcetera. Those operating conditions are very sensitive input parameters in 1D engine simulation which can affect the cycle simulation and in turn give bad prediction of performance parameters.

Table 1: Optimum value of parameter 'a' at full-load operating points

No.	Full-load (WOT)		
	Operating Point (rpm)	Shape Parameter 'm' (-)	Optimum Value of Parameter 'a' (-)
1.	1000	2.6	3.69
2.	1500	2.6	2.42

3.	2000	2.6	2.28
4.	2500	2.6	2.6
5.	3000	2.6	1.61
6.	3500	2.6	-1.03
7.	4000	2.6	-2.10

Table 2: Optimum value of parameter 'a' at part-load operating points

No.	**Part-load**		
	Operating Point (rpm)	Shape Parameter 'm' (-)	Optimum Value of Parameter 'a' (-)
1.	1000	2.6	4.64
2.	1500	2.6	2.75
3.	2000	2.6	2.63
4.	2500	2.6	1.58
5.	3000	2.6	2.17
6.	3500	2.6	1.41
7.	4000	2.6	0.11
8.	4500	2.6	-0.67
9.	5000	2.6	-0.31

Table 3: Optimum value of heat transfer factor at part-load operating points

No.	**Part-load**	
	Operating Point (rpm)	Optimum Value of Heat Transfer Factor (-)
1.	1000	8.9
2.	1250	23.5
3.	1500	28.1
4.	1750	38.5
5.	2000	38.5
6.	2250	36.8
7.	2500	35.6
8.	2750	32.3
9.	3000	32.7
10.	3500	30.3
11.	4000	28.8
12.	4500	27.3
13.	5000	27.6

3.2 ANALYSIS ON INTAKE MANIFOLD TEMPERATURE TUNING AT PART-LOAD

The way to control the intake manifold temperature is by controlling the intercooler performance. One way of doing this is by tuning the ‘heat transfer factor’ parameter in the intercooler element. This heat transfer factor is able to specify the cooling performance of the engine model. The aim of this tuning work is to determine the optimum heat transfer factor value of the Proton CamPro engine model at part-load condition. The heat transfer factor of the engine model has been optimized for each operating point by comparing the output intercooler outlet temperature with the experimental data. The simulation has been performed several times with varied preliminary value of heat transfer factor which were distributed randomly for every operating point. The simulation was ended and the optimum heat transfer value were recorded when the output intercooler outlettemperature had matched well with the experimental data by complying the acceptable difference of 2 degree Celsius. Table 3 shows the optimum heat transfer value used in matching the output intercooler outlet temperature with the experimental data as shown in Figure 6.

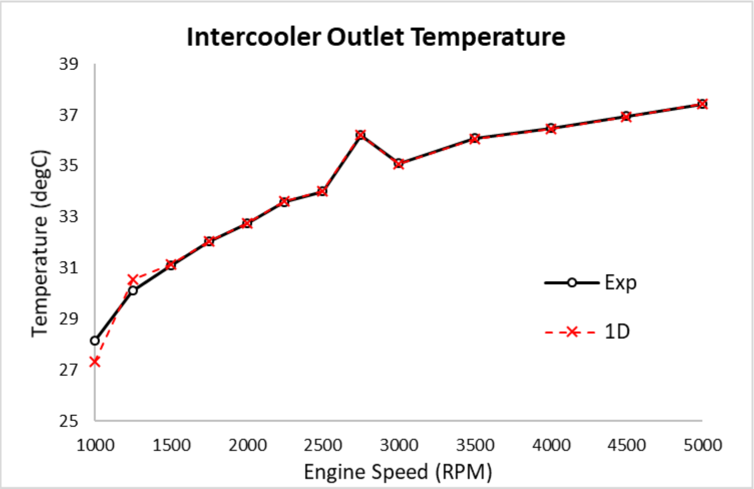
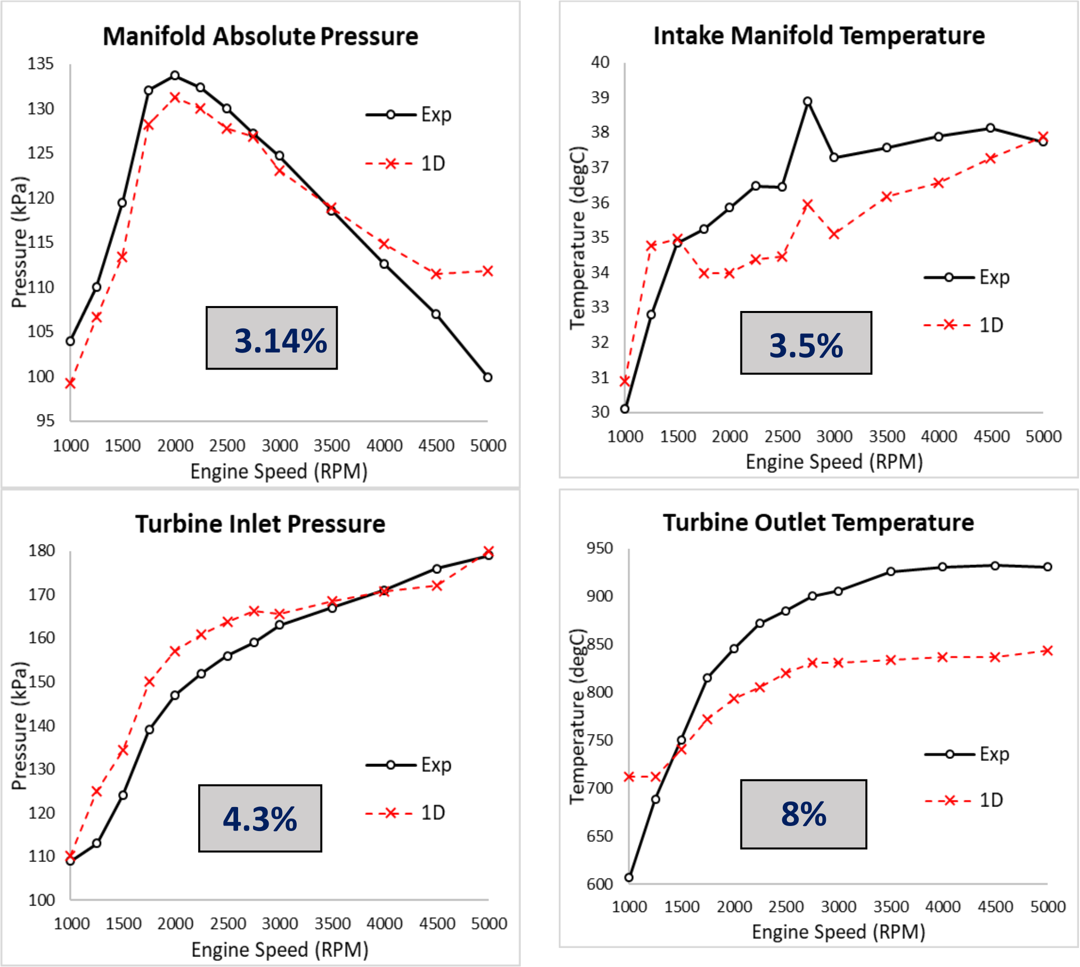


Figure 6: Comparison of intercooler outlet temperature curves at part-load condition



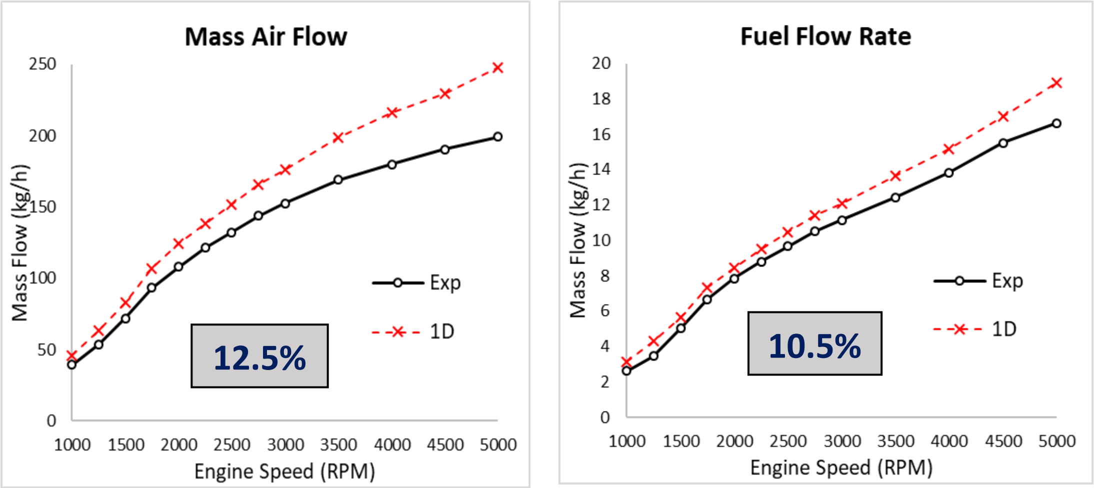


Figure 7: The curves of engine performance parameters at part-load condition

For the validation process, several performance parameters have been chosen to evaluate the ability of the engine model, in predicting the output engine performance as theexperimental data based on the achieved percent error. The percent error parameter has been calculated for each performance parameter as shown in the Figure 7. Figure 7 shows the comparison between output performance parameters with experimental data. Based on Figure 7, it shown that majority of the output performance parameter curves seem plausible even it did not perfectly matched. The percent error has been calculated for eachperformance parameters. From the calculations, 4 performance parameters were found to achieve the percent error below 10% and the remaining are very close to the value. The 4 performance parameters are manifold absolute pressure (MAP), intake manifoldtemperature, turbine inlet pressure and turbine outlet temperature with the percent error of3.14%, 3.5%, 4.3% and 8%, respectively. The remaining parameters are mass air flow andfuel flow rate with the percent error of 12.5% and 10.5%, respectively. As shown in the Figure 4.4, the output mass air flow appears too deviant from the experimental data compared to other performance parameters. This is due to the same problem occurred for the previous combustion model tuning, where several operating conditions in cylinder element which did not reach the optimum value during the simulations such as in-cylinder wall temperature, heat release characteristic and etcetera. Overall, the engine performance is well predicted as it complies the allowable error band proposed by previous researches which is 10% and the most accurate performance parameter prediction is obtained by manifold absolute pressure with 3.14% error. However, major discrepancy is noticeable for several engine performance parameters especially on mass air flow and fuel flow rate.

CONCLUSION

In this thesis, a Proton 1.6-litre CamPro 4-cylinder turbocharged gasoline engine have been modeled using AVL BOOST. The developed engine model was used to validate the engine performance parameters from the simulation results with experimental data. From the intake manifold temperature tuning, several engine performance parameters have been validated with experimental data. Overall, there is no any output performance parameter which perfectly matches the experimental data but the achieved percent errors are still acceptable. Since the deviation in this study is within 10% band, it can be concluded that the engine model is able to represent real engine conduct. By referring to the objective of this project which is to predict the steady-state performance at full and part-load conditionsfrom 1000 to 5000 rpm, it can be conclude that the engine model had meet the target.

From this study, several meaningful recommendations are made to increase the accuracy level (<5%) of the simulation model for further application in other studies. Firstly, the turbocharger and air flow matching should be improved. In general, the performance of SI engines is very sensitive to air flow. The large deviation of the air flow implies that turbocharger is not operating correctly. Secondly, combustion duration and in-cylinder heat transfer factor should be carefully considered in combustion tuning process. The different engine speeds and loads will change the physical combustion time and heat loss. It could be calculated from heat release analysis with in-cylinder pressure for known geometry. Thirdly, exhaust tuning is also required not only intake tuning. Exhaust gas temperature has strong effect on turbine and turbocharger operation. Also, to reduce the effort and time on tuning process with the increasing number of the tuning parameter, it is suggested to develop systematic approach to tune each parameter.

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