Optimization of Fuel Consumption of a SI Engine Using Variable Valve Timing and Variable Length Intake Manifold Techniques

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Article Info

Abstract

According to the world crisis about fuel consumption and environmental concerns regarding toxic emissions of internal combustion engines, the engines with higher efficiency and lower fuel consumption have been a topic of research in last decades. In this study, variable valve timing (VVT) and variable length intake manifold (VLIM) techniques are used to optimize the fuel consumption of an SI engine. At first, all components of engine are modeled in GT-POWER and a comparison with experimental results is performed to confirm the accuracy of the model. Then, the discrete-gird algorithm is employed to optimize the parameters in GT-POWER. The results obtained indicate that optimal valve timing and intake manifold length significantly reduces brake specific fuel consumption (BSFC).

1. Introduction

The universal regulations governing the control of green-house gas emissions are now being tightened so that vehicle manufacturers have to satisfy these constraints. The reduction of engine fuel consumption becomes a primary requirement to meet current and future emission legislations [1]. For this purpose, several methods such as fast combustion, lean burn, variable valve timing and gasoline direct injection have been suggested in the literature. Variable valve timing is one of the most efficient methods which not only reduces fuel consumption and engine emissions but also, solves low end torque problem.

In automotive applications, the variable valve timing was first developed by Fiat in late 1960 [2]. Considering the ability of the system, it was soon used by other companies like Honda, General Motors, Ford and other automobile manufacturers. Liguang et al. [3] examined intake and exhaust valve timing effects on spark ignition engines. They experimentally investigated the effect of these two factors on power, torque, fuel consumption and the HC emissions. Bohac et al. [4] studied the effect of variable exhaust valve opening (EVO) and exhaust valve closing (EVC) on HC emissions reduction. They studied the effect of different EVO and EVC timings under steady-state and start-up conditions, and concluded that the early EVO could be helpful for engine HC emission reduction in steady-state conditions but not in start-up condition.

Shayler [5] experimentally investigated the effects of intake and exhaust valves timing on remaining output gases. He concluded that timing of intake and exhaust valves will have considerable influence on the extent of fuel and fresh air entrance to the combustion chamber. Leroy et al. [6] conducted a series of research into controlling intake air path in an engine having a variable valve system without EGR. They considered internal EGR effect in engines having variable valve systems and studied their effects on reducing fuel consumption and emissions as well as negative effects of increased internal EGR on torque and air-fuel ratio. They presented a new control way by which beneficial effects of variable valve system would be added and its negative effects would be reduced. Wu et al. [7] optimized valve timing of a gasoline engine using a neural network algorithm. The result of this study was to reach optimal timing by using neural network in a variable valve system engine. Therefore a mathematical model of the target engine has been made,

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then the model was validated by using experimental information and also the constants and performance zone of engine have been realized. Then to maximize the output torque, timing of valves is changed and the best timing in each speed in full throttle condition using a neural algorithm was determined.

Variable valve systems also are able to enforce considerable effects on cylinder processes. The most important advantage of a variable valve system that is known in reducing both pumping wastes and fuel consumption has been considered due to this system [8]. As optimization is a very important issue in all sciences and fields, researchers in all sciences have used different kinds of optimization algorithms. Some examples of using conjugate gradient, sensitivity analysis [9] and Quasi-Newton optimization algorithms that are considered in this study have been provided in previous work.

In 2007, Ceviz [10] examined the effect of manifold calm chamber volume on engine function and emission. He concluded that the brake function and engine indicator, the pressure flow and pollutants such as CO, CO2 and HC are changed by changing the manifold intake volume. Braking torque at speeds between 1,700 to 2,500 rpm is increased by increasing the calm chamber volume. Also, the increase in volume of the calm chamber will make mixture of fuel and air more diluted. In 2010, Ceviz et. al. [11] designed a spark ignition engine with manifold variable in term of the length of calm chamber. The results of this research showed that changing the length of the intake manifold improves the engine function especially at low rpm and high loads. These driving conditions (low rpm and high load) are occurred more in urban driving and are included most of driving cycles. According to this research, the manifold length for low engine speeds (manifold relaxation chamber) should be increased and the length should be reduced for higher engine speeds.

In 2014, Potul et. al. [12] examined the changes of manifold intake length. In this study, the generation of expansion and compression waves in the manifold intake and the beneficial use of these waves in favor of the volumetric efficiency of the motor were focused. In this study, the effect of resonance in these wave and the change in the intake manifold on the engine performance is studied and simulated analytically and. The results of this research showed the engine speed where the maximum torque occurs significantly is changed with changes in the length of manifold intake. To increase the engine torque at low speeds, the length of manifold intake is increased and at high speeds this would be decreased.

One of the ways that determines amount of power, fuel consumption and engine efficiency is to obtain maximum amount of air into the cylinder during each cycle. So, as far as possible the loss of engine volumetric efficiency should be reduced by appropriate solutions. To achieve this goal, several methods are recommended. Some of these techniques include Increasing the diameter of the air intake valve and exhaust (with consideration of strength cylinder material), increasing the number of inlet valves to 2 or 3, designing manifolds for high performance, software changes such as optimization of the timing of the inlet and outlet valves and ignition angle etc. among guidelines presented in this study, to improve volumetric efficiency, optimizing the timing of the inlet and outlet valves and intake manifold length was considered. Because with lowest cost, to acceptable results could be achieved in this case. Adoption of Intake valve timing and appropriate length of manifold at different situations based on engine speeds and engine operating conditions lead to improve engine performance and reduce fuel consumption and emissions of the engine. This increases the time of breathing in high and restore burned gases to the intake internally, as well as solve the problem of low torque at low rpm and low power in high speed.

In the next part, engine XU7JP4 / L3 is simulated in GT-POWER software and all engine components including inlet and outlet manifolds, inlet and outlet valves, injectors, all components of the cylinder and crankcase, catalytic converter, the exhaust etc… are modeled. Then with regard to the possession of the experimental results, the model was used to validate the results. To validate the results of model, comparison of torque and power compare is used.

2. Using the optimization tool of GT-POWER software

GT-POWER Software has a tool to optimize the output by changing one or more parameters. The optimal amount can be maximum, minimum, or a target value. In this thesis, the purpose is to minimize brake specific fuel consumption at any rpm by changing the optimization parameters including the angles of the valves and the intake manifold. This optimization was carried out for the speed of 1500, 2000, 2500, 3000, 3500, 4000, 4500, 5000, 5500 and 6000.
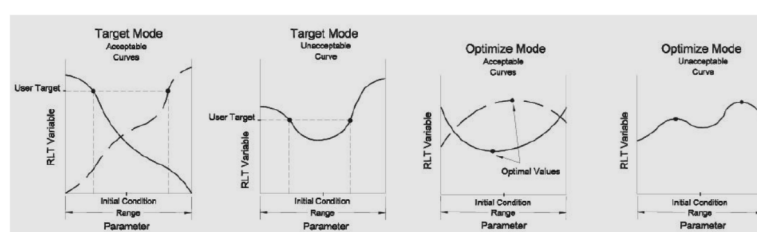

Figure 1. Acceptable and unacceptable curves for optimization by GT-POWER software tool

For optimization tools, optimal value should be unique; otherwise, there is no respond. In the following figure, acceptable and unacceptable curves of for this type of optimization can be seen.

Optimization method taken in this thesis is a discrete grid method. In this method, search range in each repetition is halved to finally reach to the optimum value (maximum or minimum). This method is very powerful and always leads to reply if the curve has only one answer. In this study, the main parameter is associated with fuel consumption of engines that achieve a minimum engine speed [13].

3. Validation of the model

To validate the results of the, simulated engine model in GT-POWER software, the experimental results have been used. For this validation, comparison of the results of torque and power model with experimental data is used. Available laboratory information is based on the information obtained from dynamometer of research and development engine IranKhodro Company (IPCO) that the results are summarized in table 1.

Table 1. Laboratory Results Obtained From the Dynamometer of IPCO Company [14, 15]

RFM (rpm)	STRQ (N.m)	SPOW(kw)	FCON kg/h	ISOCF
1500	125.2	19.64	4.6	1.129
2000	126.3	26.41	6.2	1.129
2500	142.0	37.21	8.9	1.130
3000	140.5	44.09	10.4	1.132
3500	139.5	51.17	12.8	1.135
4000	136.3	57.16	15.0	1.137
4500	130.4	61.51	17.0	1.138
5000	122.9	64.41	18.2	1.138
5500	116.9	67.41	20.5	1.139
6000	109.3	68.75	21.1	1.140

In this section, we examine and compare the data and information obtained of the model and laboratory information.
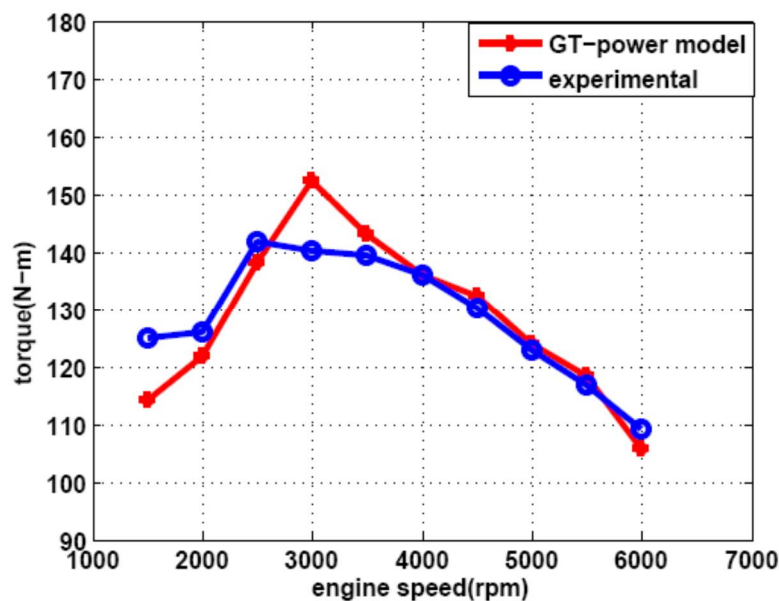

Figure 2. Validation of results of simulated and laboratory torque

As shown in figure 2, the behavior of the model and the laboratory information are similar. In the high speed, model can provide a good approximation of the actual performance of the engine, but at low speeds it is faced with a higher error. The percentage of mean error between the torque and the obtained torque from the laboratory is 2.43.
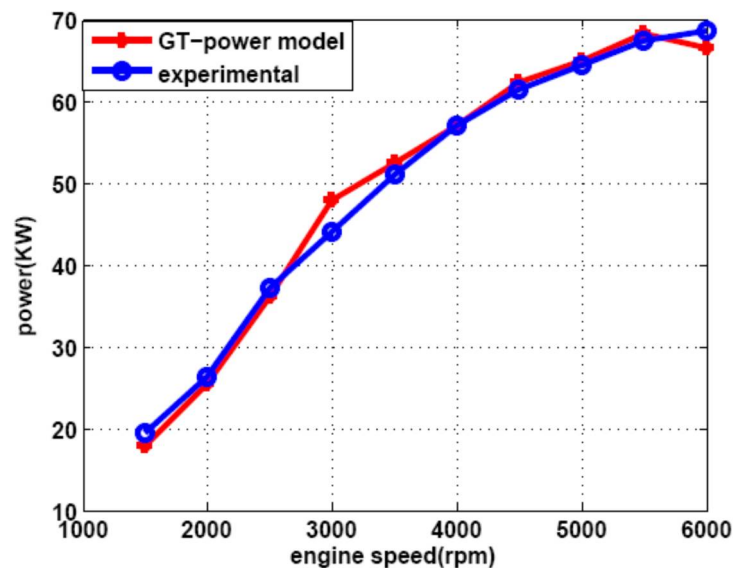

Figure 3. Validation the results of simulated and laboratory power

Also shown in figure 3, power in down speed is low and at high speeds is more than the measured power in the laboratory. The percentage of mean error between model power and power of the laboratory is 1.51.

From these results it is concluded at the below speed, model has greater error of the model, and the average error between curves of torque and the power of simulation laboratory results and is about 1.92 percent. The difference between the curve of simulation and experimental because the fuel is used in the simulation has the characteristics of a standard gasoline, while specifications of gasoline used in Iran is not standard. In general, the results of the analysis have good accuracy.

4. Results and discussion

Given the above, the optimization basis is on the sensitivity of model output to input changes. Prepared model based on the sensitivity of outputs to inputs tries to change the inputs closest to adopt objective function. Here, input parameter is opening timing and closing the inlet and outlet valves and intake manifold length and output parameter is brake specific fuel consumption.

In this section, GT-POWER coupled software and discrete-grid algorithm were used to optimize the opening and closing angles of the inlet and outlet valves and the length of intake manifold to reduce brake specific fuel consumption. Also the results obtained are compared with the results of the basic model to show the impact of the optimum angles of valve and length of the intake manifold to reduce fuel consumption.

4.1. Univariate optimization

In this study, initially a univariate optimization was conducted. univariate optimization means that the fuel consumption is considered to be only a function of a variable. Here, these variables are the intake valve opening angle (IVO), the angle of the intake valve closing (IVC), exhaust valve opening angle (EVO), angle of exhaust valve closing (EVC) and the intake manifold.

Optimization algorithm finds the optimal amount of minimized fuel consumption by changing these variables.

4.1.1. Optimization of angle of intake valve opening

In figure 4, the angle of the intake valve opening optimized according to the engine speed can be seen. This angle is cam angle is measured relative to the top of dead center (TDC). As can be seen, increasing the engine speed, this angle opens earlier. This behavior can be justified so that by increasing the engine speed, the time available for suction process is reduced and by earlier opening of this valve, the lack of time will be compensated.
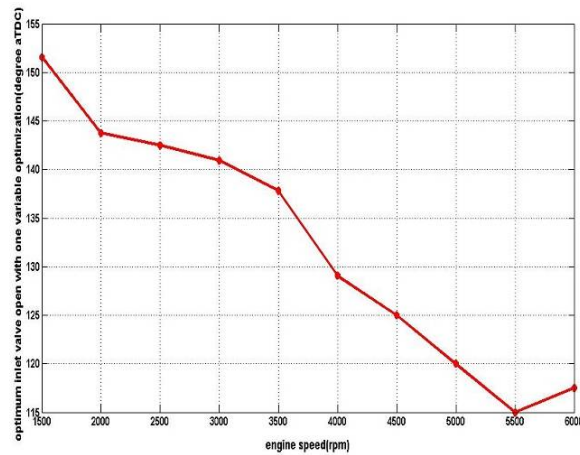
Figure 4. The optimal angle of the intake valve opening in term of engine speed by univariate optimization

In figure 5 optimum results of fuel consumption with variable of intake valve opening angle rather engine speed is observed. Percent of improvement in fuel economy by optimizing these parameters (angle of the intake valve opening) is about 0.446.
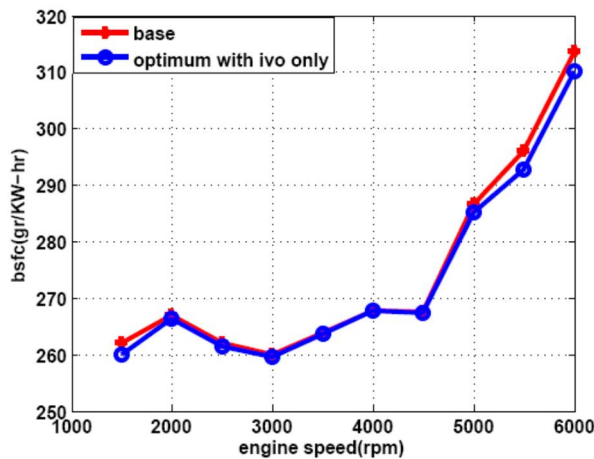

Figure 5. Optimized fuel consumption in term of engine speed by optimizing intake valve opening angle

In figure 6 improved results of the torque rather the engine speed can be seen. As can be seen, the percent of improvement of torque in low speed is greater than the high speed.
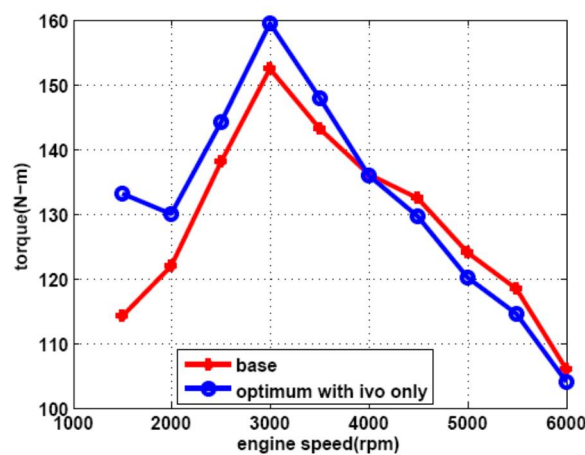
Figure 6. Optimized torque in term of engine speed by optimizing intake valve opening angle

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4.1.2. Optimization of the angle of the intake valve closing

Figure 7 shows optimized intake valve angle closing according to the engine speed. As seen, increase in engine speed will be closed later this angle. This behavior can be justified so that by increasing the engine speed with the later closure of the valve, lack of time due to the increase in engine speed is compensated and more air is entered into the engine and increase the engine power due to the increased intake air to the engine specific fuel consumption (power / fuel consumption = bsfc) is reduced. Also, diagram (7) shows that the angle is not changed between the 5500 and 6000 rpm.
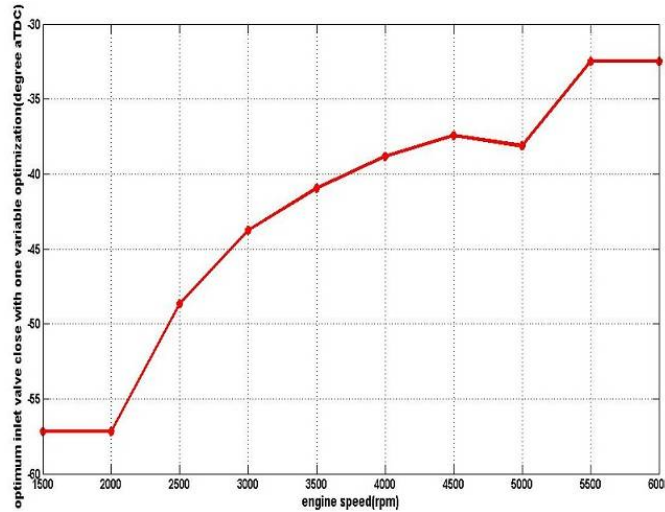

Figure 7. The optimal angle of the intake valve closure in univariate engine optimization

In figure 8 optimum results of fuel consumption with intake valve closing angle variable in term of engine speed is observed. Percent of improvement in fuel economy by optimizing these parameters (angle of the intake valve closure) is about 2.253.
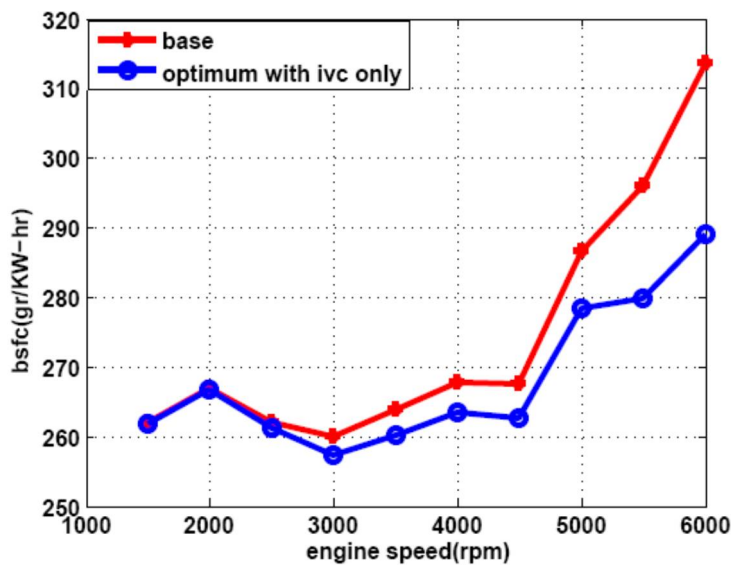

Figure 8. Optimized fuel consumption in term of engine speed by optimizing angle of the intake valve closing

In figure 9, improved results of torque compared to the engine can be seen. As can be seen, in contrast to optimize intake valve opening angle, the percent of torque improvement at higher rpm is more than low rpm. This means that the effect of closing the intake valve angle on engine performance at high speeds is more than low speeds.
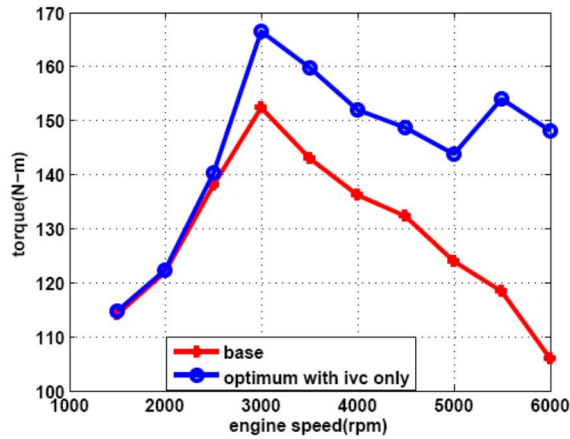
Figure 9. Optimized torque according to engine speed with optimizing the angle of the intake valve closing

4.1.3. Optimization of exhaust valve opening angle

In figure 10, optimized angle of the exhaust valve opening based on the engine speed can be seen. As can be seen, with increasing rpm this angle opens earlier, this behavior can be justified so that by increasing engine speed, this angle opens up earlier to leave combustion products by cylinder and with burnt gases discharged better, more air into the engine in the next cycle, resulting in increased horsepower and reduced specific fuel consumption. It was also observed that around 5500 rpm onwards this angle does not change. Because if this angle is more than a certain level, open early stage, and does not affect the power of the combustion piston is well and fully.
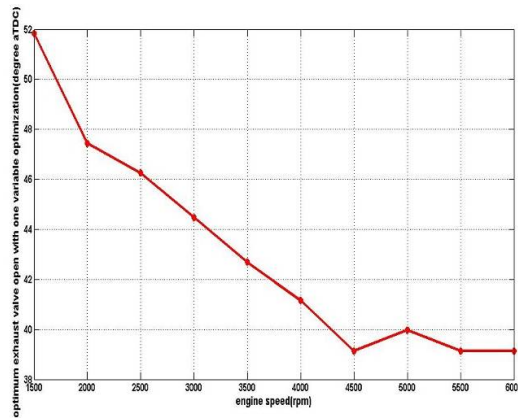

Figure 10. The optimum angle valve opening output in univariate optimization

In figure 11, the optimum results of fuel consumption is observed by exhaust valve opening angle variable toward engine speed. Percent of improvement in fuel economy by optimizing this parameter (exhaust valve opening angle) is about 2.17.
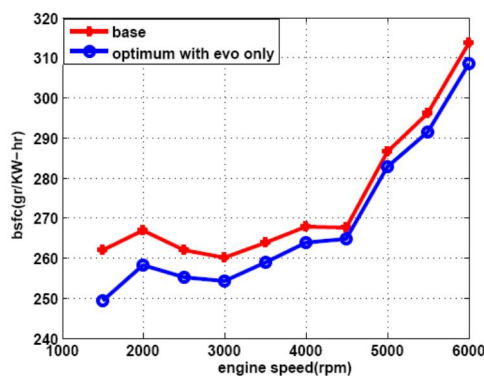

Figure 11. Optimization of fuel consumption in term of engine speed by optimizing exhaust valve opening angle

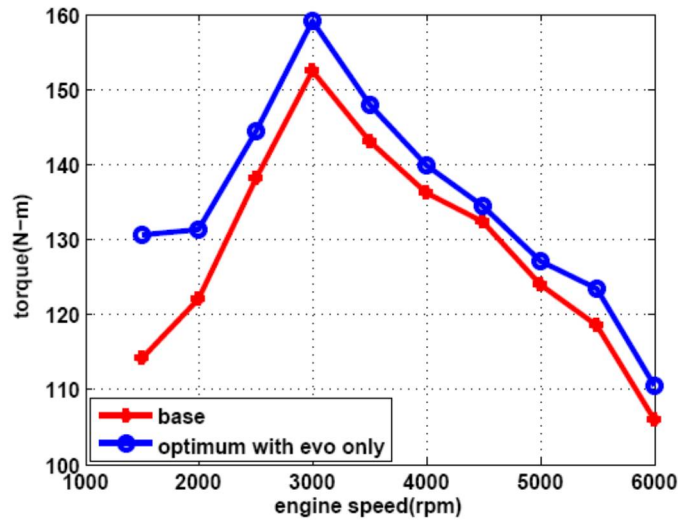In figure 12, the improved results of torque compared to the engine can be seen.

Figure 12. Optimized torque according to engine speed by optimizing exhaust valve opening angle

4.1.4. Optimization exhaust valve angle closure

In figure 13, optimized angle of the exhaust valve closing can be seen according to the engine speed. This angle, as can be seen is closed by increasing engine speed to discharge burned gas better and compensate lack of time due to the increase in engine speed. It was also observed that from around 5500 onwards, this angle would not be changed. Cause of this can be expressed in this way that of a certain extent depending on the angle if its late stage density continues to influence the next cycle and pressure and combustion temperature reduces the cycle and thus reducing engine power and increases specific fuel consumption.
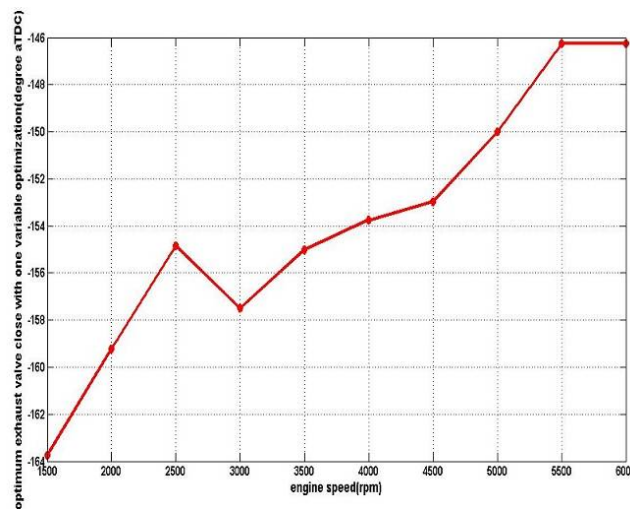

Figure 13. Optimal angle of exhaust valve closure in term of engine speed by unvariate optimization

In figure 14, optimum results of fuel consumption can be observed, by exhaust valve closure variable rather the engine speed. Percent of improvement in fuel economy by optimizing the parameters (exhaust valve closing) is about 1.803.
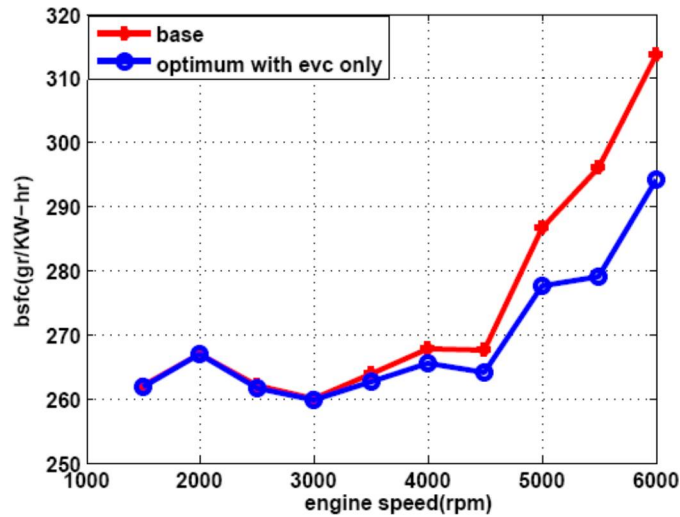
Figure 14. Optimization of fuel consumption in term of engine speed by optimizing exhaust valve closure angle

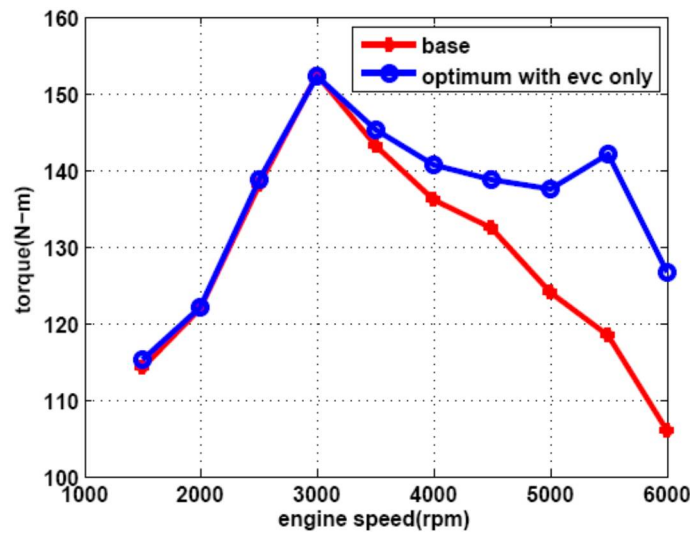In figure 15 optimal results of torque than engine rpm is shown.

Figure 15. Optimized torque in term of engine rpm by optimizing exhaust valve closure angle

4.1.5. Optimization of intake manifold length

In figure 16, the optimized intake manifold according to engine rpm can be seen. Intake manifold in this study is length of intake manifold calm chamber. As can be seen, in the low speed, manifold is high and increase engine rpm to be reduced during by middle speed. After middle speed, the length will be raised and at high speed, this length is reduced again. This change in manifold length can be divided into two main sections. In the low speed, this length is more than high speed.

Cause of this behavior can be explained as follows. In low speed, air flow rate is low and as result flow regime is laminar and by increasing manifold length (length characteristic of Reynolds number) laminar flow regime is changed to turbulent. With turbulent flow regime, better mixing of fuel and air is improved, and combustion quality is increased and thus increasing engine power and special fuel consumption is reduced. At high speeds due to the high air velocity, friction declines in the intake manifold (according to relationship $h_f = f \dfrac{L}{D} \dfrac{V^2}{2g}$) is increased. To decline the loss, manifold

length (L) is reduced to increase engine power and reduce specific fuel consumption by reducing frictional losses in the volumetric efficiency.
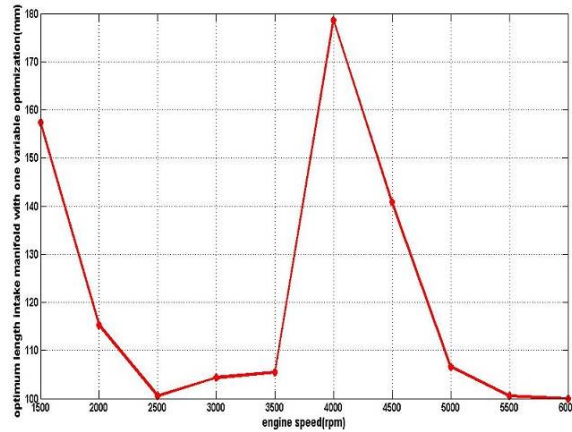
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Figure 16. The optimal length of intake manifold in term of engine speed by unvariate optimization

In figure 17, optimum results of fuel consumption is shown by intake manifold length variable rather to the engine rpm. Percent improvement in fuel economy by optimizing the parameters (length intake manifold) is approximately 0.29.
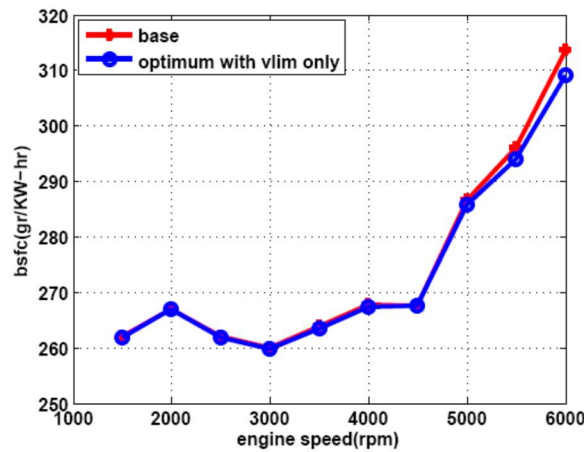

Figure 17. Optimization of fuel consumption in term of engine rpm by optimizing length of intake manifold

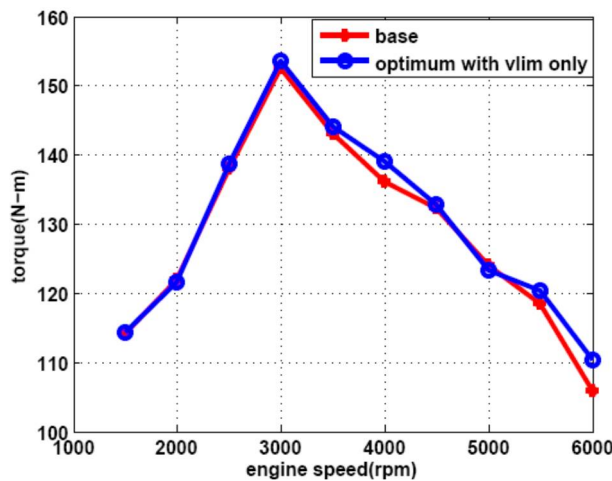In figure 18, improved results of torque compared to the engine can be seen.

Figure 18. Optimized torque according to engine rpm by optimizing length of intake manifold

5. Conclusions

In this study in the first stage, the engine model was prepared in GT-POWER and the experimental results were used to validate the model. Percentage error of the mean between torque and torque version obtained from the laboratory was 73.3. Also mean error of the brake specific fuel consumption obtained from laboratory models and brake specific fuel consumption is about 71.2. At high speeds model has greater errors. In the next step to optimize brake specific fuel consumption, the timing for opening and closing the inlet and outlet valves and intake manifold length optimization algorithm discrete-grid was calculated. After the necessary calculations, the following results were obtained:

- With increasing engine rpm inlet valves open sooner. This behavior can be justified by increasing the engine rpm is reduced and the time available for suction process before opening of this valve this lack of time will be compensated.

- With increasing engine rpm, the intake valve must be closed later. This behavior can be justified by increasing the engine rpm with the later closure of the valve, lack of time due to the increase in engine speed by being more air into the engine and increase the engine power due to the increased intake air to the engine specific fuel consumption (power / fuel consumption = bsfc) is reduced. It can be seen between the 5500 and 6000 rpm, this angle is not certain.

- Effect of closing the intake valve angle on engine performance at high speeds is more than low speed.

- With increasing engine rpm, exhaust valve should open earlier. This behavior can be justified by increasing engine rpm, this angle opens up earlier to remove combustion products of cylinder and burnt gases are exchanged better and more air enters into the engine in the next cycle, resulting in increased horsepower and reduced specific fuel consumption. This angle does not change around 5500 rpm onwards. Because if this angle is more than a certain level, open early stage and affect the power and combustion power is not entered to piston well and fully.

- With increasing engine rpm, exhaust valve must be closed later discharge of burnt gases better and to compensate the lack of time due to the increase in engine speed. The angles are not changed from 5500 rpm onwards. Cause of this can be expressed in this way, that of a certain extent depending on this angle if its late stage density continues to affect the next cycle and next reduce the pressure and temperature of the combustion cycle, resulting engine power is reduced and specific fuel consumption is increased.

- At low rpm, the length of manifold has increased and increasing engine rpm in average rpm of this length is reduced. After average rpm, the length will rise again this length is reduced again in high rpm. This regime manifold length can be divided into two main sections. In low rpm, this length is more than high rpm.

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