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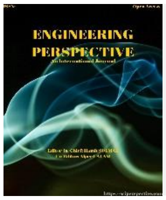

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Simulation of The Effects of Valve Timing Misalignment on Performance in Spark Ignition Engines

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ABSTRACT

Engine performance can be improved by changing the valve opening (or closing) timing without any cam profile changes. In this study, a simple simulation model was created for valve timing misalignment, which is an assembly defect in the engine. Due to misalign, the opening angles of the valves have been changed between +20 degrees and −20 degrees compared to the normal opening angles. The engine performance resulting from this advanced and retarded valve timing was examined for a four-stroke, spark ignition, single-cylinder engine with an engine volume of 393 cc. In this study conducted for the 1000-7000 rpm engine speed range, first the in-cylinder pressure data were examined in detail and then the general engine performance parameters were examined. Accordingly, opening the valves earlier than necessary at low and medium engine speeds increases the maximum in-cylinder pressure, and at high engine speeds, it reduces the maximum in-cylinder pressure due to excessive decrease in volumetric efficiency. It was observed that the volumetric efficiency, which was 0.89 at medium speeds, decreased to 0.70 due to misalignment. Regardless of whether the misalignment is positive or negative, pressure fluctuations increase during the valve lapping process. Maximum braking torque occurs at medium engine speeds. Positive misalignment reduces braking torque, especially for low and high engine speeds. However, especially at high speeds, negative misalignment reduces the pumping torque. While the pumping torque for high engine speeds was −3.78 Nm, it increased up to −5.04 Nm due to positive misalignment. Whether it is positive misalignment or negative misalignment, brake specific fuel consumption tends to increase in both cases. At low and medium engine speeds, negative misalignment or positive misalignment always increases residual gas fraction. As a result of the study, it was seen that misalignment negatively affected engine performance. However, it is seen that the value accepted as reference is the optimum value for the operating speed range of the engine. With this study, it has been understood that valve timing, as well as valve system design, is vital for engine performance.

Keywords: Engine simulation; misalignment; performance; valve timing

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1. Introduction

Perhaps humanity's most perfect invention, which has a greater impact on society, economy, and environment, is the reciprocating internal combustion engines [1, 2]. Although many researchers have made significant contributions to the development of internal combustion engines, the historic breakthrough of Nicolaus Otto (1876) and Rudolf Diesel (1892) in the development of the spark ignition engine and compression ignition engine has been recognized worldwide [1-3] As a result of the widespread use of these engine technologies, 25% of the world's oil is consumed. For this reason, it is estimated that 10% of the world's greenhouse gases originate from internal combustion engines [4].

Internal combustion engines operate based on cycles in which sequential processes occur. A series of mechanical and electronic components are needed for the formation of these cycles. The main purpose of engine cycles is to obtain work. The process by which work is obtained is known as the expansion process [5-11]. In studying cycles thermodynamically, the focus is on obtaining work. In ideal thermodynamic cycles, intake and exhaust processes are neglected. However, the amount of work that can be achieved in a cycle is closely related to the geometric dimensions of the engine, the start of combustion and the performance of processes other than the expansion process. The gas exchange process is also an important parameter for a current engine. Because the performance of the intake process is very important to increase the exhaust process and energy input to start a new cycle. The concept of increasing energy input can essentially be explained by the expression volumetric efficiency [10-15].

The amount of air sucked into each cylinder determines the amount of fuel that can be burned. Therefore, it is a very important design goal for the system to be able to flow as much air as possible into each cylinder (capacity to breathe at a certain rate). The degree to which burnt gases remaining from the previous cycle are expelled from the cylinder also affects the air flow entering the cylinder. For this reason, the exhaust process is at least as important as the intake process [5-11].

There are many parameters that affect volumetric efficiency. Some of these can be listed as quasi-static effects, flow friction in the intake and exhaust system, airflow choking in the intake valve, in-cylinder heat transfer, and overfilling. Apart from these, valve timing as a parameter also directly affects volumetric efficiency [1, 10-12]. All these parameters are design features for an engine.

The flow characteristic is different for each engine speed. To achieve high volumetric efficiency, separate valve timing must be designed for each engine speed. For this purpose, variable valve timing mechanisms are used in today's engines and thus the desire for high volumetric efficiency can be realized. Although there are various strategies for variable valve timing, the most used strategy is cam phase shifting. Continuously adjusting the phase of the intake cam and exhaust cam relative to the crankshaft is the most common approach. This approach uses an intake valve shut-off adjustment range of approximately 40 degrees (± 20 degrees). With this method, approximately 5% torque increase can be achieved compared to a conventional engine [1, 16].

Valve timing is characterized by both the time the valves remain open and the time the valves open/close. For this reason, modified camshafts are preferred for a change in performance, especially in the engines of vehicles used for racing or hobby.

There are studies on valve timing in the literature. Liu et.al. investigated the effects of intake valve timing misalignment on maximum volumetric efficiency and backflow in a single-cylinder diesel engine. In this paper, it was mentioned that the closing timing of the intake valve directly affects the amount of backflow and the amount of fresh filling, and for this purpose, only the effect of the change of the intake valve closing timing was examined in 1D and 3D simulation models. As a result, he reported that the emergence of backflow is a gradual process, and that backflow is present when the engine reaches its maximum volumetric efficiency. Misalignment has been stated to approach zero only if the average valve closing speed approaches infinity [17]. Bücker et.al. conducted a study on in-cylinder flow control through variable valve timing in their paper. In this paper, it is mentioned that the in-cylinder flow is controlled by the cam phasing method on the intake camshaft. In this way, it is stated that volumetric efficiency will increase, and pumping loss will decrease. In this study, the underlying flow phenomenon, namely the effect of variable valve timing on tumble development and turbulent kinetic energy, is analyzed. The flow field was examined at a series of early, ambient, and late suction valve opening positions in the suction and compression processes. Variable valve timing has been shown to have a strong effect on mean vorticity and the local and temporal distribution of kinetic and turbulent kinetic energy. Additionally, it has been reported that the amount of turbulent kinetic energy in the intake stage is linked to intake valve opening, which is important for fuel injection and mixing [18]. Abidin et.al. examined the effect of camshaft rating on performance in a passenger vehicle. What is meant by camshaft gradation here is the coincidence of the markings determined for the synchronization of the crankshaft and camshaft movements. In this study, the authors experimentally examined the effects of forward and reverse exhaust timing on performance. The results showed that the later the exhaust valve opens, the more torque and power are obtained at low engine speed [19]. Sher et.al. conducted a study on valve timing optimization in which specific fuel consumption would be minimum and engine torque would be maximum in a spark ignition engine. The basic performance parameters of the engine were calculated using a computer program that simulates the real engine cycle. When both valves and spark timings were optimized, it was concluded that the optimal timing of each valve apparently depended linearly on engine load, linearly on engine speed, while the slope depended weakly on engine load. It has been reported that because of the optimization, the maximum torque was shifted to a lower engine speed [20].

It is clear from previous papers that engine performance can be improved by changing the valve opening (or closing) timing without any cam profile changes. However, it seems that one of the main factors in this timing is engine speed. This study was created based on this context.

In this study, performance losses caused by incorrect installation of the timing mechanism during the maintenance of four-stroke internal combustion engines were investigated with a 1D simulation model. For this purpose, advance and delay conditions were created for a tested single-cylinder engine according to the reference state. Thus, the effects of valve timing misalignment on engine performance have been revealed.

2. Materials and Methods

2.1. One Dimensional Engine Model

Various licensed software are available for creating and analyzing realistic or quasi realistic simulations of internal combustion engines. In this study, a simulation program that allows 1D gas dynamics to be examined was used. Thanks to the program, the one-dimensional form of the Navier-Stokes equations governing mass, momentum and energy transfer for compressible gas flows is solved and sub models for combustion and emissions can be used [21]. Basic components in an engine were selected for simulation as shown on Figure 1.

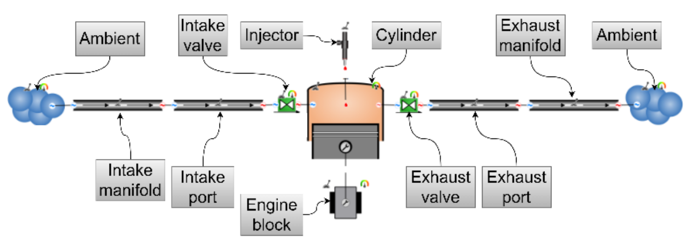

Figure 1. One-dimensional simulation model for single-cylinder engine

For the intake valve, the intake port and intake manifold are associated, and for the exhaust valve, the exhaust port and exhaust manifold are associated. Additionally, a direct injection fuel system was preferred in the model. The engine used for simulation is a research engine whose accuracy has been previously proven and tested in the simulation program. Some important features of the engine used in the model are presented in Table 1.

Table 1. Specifications of the engine used for the simulation model

Specifications	Value
Stroke	82.0 mm
Bore	78.1 mm
Conrod Lenght	150 mm
Geometric compression ratio	10:1
Stroke volume	393 cm^3
Intake valve diameter	35 mm
Exhaust valve diameter	28 mm
Intake process duration (IPD)	280°CA
Exhaust process duration (EPD)	300°CA
Intake valve opening (IVO)	330°CA
Exhaust valve opening (EVO)	100°CA
Intake valve clearance	0.15 mm
Exhaust valve clearance	0.20 mm
Intake valve lift	8.89 mm
Exhaust valve lift	8.64 mm
Rocker arm ratio	1:1
Injection timing	−100°CA
Injection duration	20°CA
Injection pressure	20 bar

In the created model, two-zone Wiebe combustion model and load compensating Woschni heat transfer model were used. The Original Woschni heat transfer sub-model views the charge as having a uniform heat flow coefficient and velocity on all surfaces of the cylinder and calculates the amount of heat transferred to and from the charge based on these assumptions. The Load Compensating Woschni heat transfer sub-model uses Woschni's modified correlation which includes indicated mean effective pressure (IMEP) compensation. Chen-Flynn Correlation was used for friction losses. The ideal gas model was adopted for compressibility. RON 95 gasoline specifications were used as fuel. The fuel/air ratio is assumed to be stoichiometric for all cases.

2.2. Valve Timing Diagram

Internal combustion engines rely significantly on valve timing diagrams to regulate the intake and exhaust processes, facilitating the engine's breathing functions. Therefore, it is necessary to determine the opening and closing timings for the intake and exhaust valves in the engine throughout the cycle. The valve timing diagram for the engine whose specifications are given in Table 1 is presented in Figure 2. Here, the exhaust valve is open between EVO (Exhaust valve opening) and EVC (Exhaust valve closing). Similarly, the exhaust valve is open between IVO (Intake valve opening) and IVC (Intake valve closing). The region between EVC and IVO is called valve overlap, and both valves are open in this angular range. As seen in Figure 2, the reference points in the valve timing diagram are TDC (Top dead center) and BDC (Bottom dead center). All angular relationships are presented according to TDC and BDC. For this reason, the camshaft and crankshaft must be engaged correctly. In case of an incorrect engagement, the valve timing diagram changes. However, the angle value between EVC and IVO does not change at all. For example, in a situation where EVC closes late, IVO also opens late, and in a situation where EVC closes early, IVO also opens early.

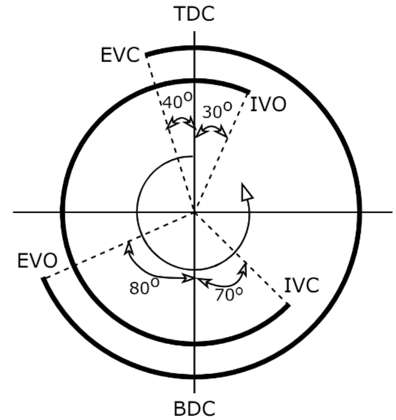

Figure 2. Valve timing diagram for reference engine

2.3. Model Parameters and Boundary Conditions

In the simulation model created, the parameters related to valve timing are IVO, EVO, IPD, and EPD. Valve overlap, EVC and IVC parameters are calculated parameters. Here, a variable (*x*) is defined for IVO and EVO next to the values in Table 2. Depending on the value of this variable *x*, IVO and EVO values become advanced or retarded compared to the values in Table 1. Accordingly, the angular relationships for valve timing are as follows. Here, the superscript * represents the values modified by variable *x*.

$$\mathrm{IVO}^* = \mathrm{IVO} + x \quad (1)$$

$$\mathrm{IVC}^* = \mathrm{IVC}^* + \mathrm{IVD} \quad (2)$$

$$\mathrm{EVO}^* = \mathrm{EVO} + x \quad (3)$$

$$\mathrm{EVC}^* = \mathrm{EVC}^* + \mathrm{EVD} \quad (4)$$

Here there are three possible cases for variable: $x < 0$, $x > 0$ and, $x = 0$. According to this:

- If $x < 0$, it means the valves open early (advanced case).
- If $x > 0$, it means the valves open late (retarded case),
- If $x = 0$, the valves open at the reference value (ideal case).

The expression of these three situations in the valve timing diagram is as in Figure 3.

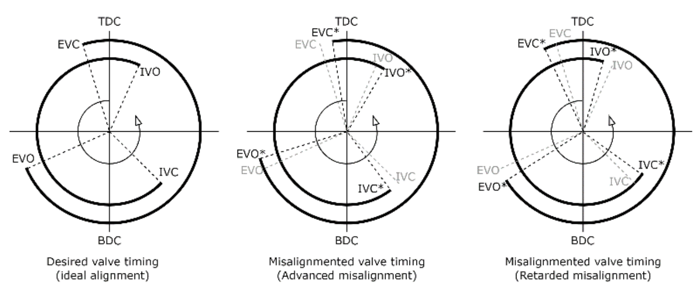

Figure 3. Valve timing misalignment cases

If you notice in Figure 3, the valve timing change is called misalignment. Because this angular misalignment occurs not to change engine performance but due to incorrect assembly.

For this study, it was assumed that the *x* value could range from −20 degrees (crank angle) to 20 degrees and solutions were made in 5 degree steps. Accepting that the engine speed can be changed from

1000 rpm to 7000 rpm, solutions were made in 1000 rpm steps. In addition, brake torque, pumping torque, residual gas ratio, brake power, brake specific fuel consumption, volumetric efficiency and exhaust temperature were used as performance parameters.

3. Results and Discussion

Performance losses due to incorrect installation of the timing mechanism during the maintenance of four-stroke internal combustion engines were examined on a 1D simulation model of a spark ignition engine and the following results are reported.

3.1. In-Cylinder Pressure Results

The results of in-cylinder pressure variation depending on crank movement were examined for three engine speeds (1000 rpm, 4000 rpm and 7000 rpm, low, medium and high, respectively). Inset graphs were created for more detailed analysis. Inset graph ① shows the intake valve closing, inset graph ② shows the maximum pressure, inset graph ③ shows the exhaust valve opening and inset graph ④ shows the valve overlap in detail.

Figure 4 shows the in-cylinder pressure values at low engine speed (1000 rpm).

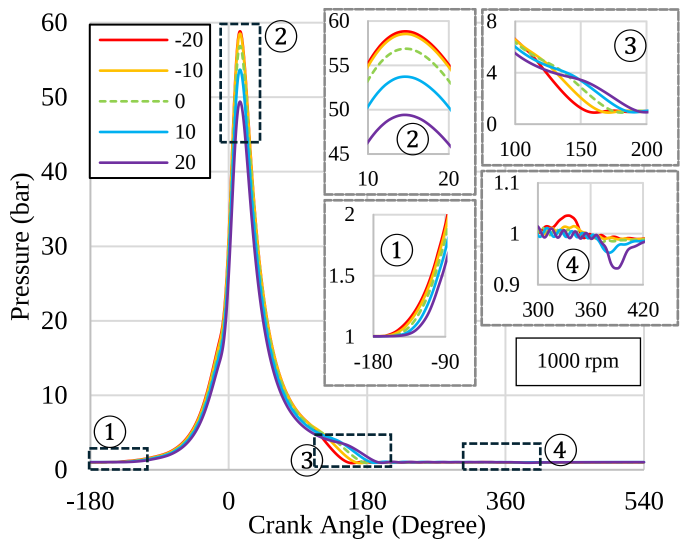

Figure 4. In-cylinder pressure for low engine speed

When Inset graph ① is examined, when the misalignment decreases, the intake valve closes early and therefore the compression process starts earlier. Thus, a higher end pressure of the compression process can be achieved. When Inset graph ② is examined, when the misalignment decreases e maximum in-cylinder pressure has also increased. In Inset graph ③, when the misalignment decreases, the in-cylinder pressure decreases faster because the exhaust valve opens earlier. In Inset graph ④, when the misalignment decreases, the valve overlap also occurs earlier. When misalignment increases, pressure fluctuation increases, albeit slightly.

In Figure 5, in-cylinder pressure values at medium engine speed (4000 rpm) are presented. When Inset graph ① is examined, when misalignment decreases, the intake valve closes early and therefore the compression process starts earlier. However, if you pay attention, the pressure difference caused by misalignment is less here. Inset graph When Inset graph ② is examined, when the misalignment decreases, the maximum in-cylinder pressure also increases. However, whether the misalignment is −10 or −20 does not change the maximum in-cylinder pressure significantly. In Inset graph ③, when the misalignment decreases, the in-cylinder pressure decreases faster because the exhaust valve opens earlier. Inset graph In graph ④, when misalignment decreases, valve overlap occurs earlier. However, pressure fluctuation increases due to misalignment. For example, when the sample value is −20, the pressure change in the valve overlap is seen to be in the range of 0.6-1.5 bar.

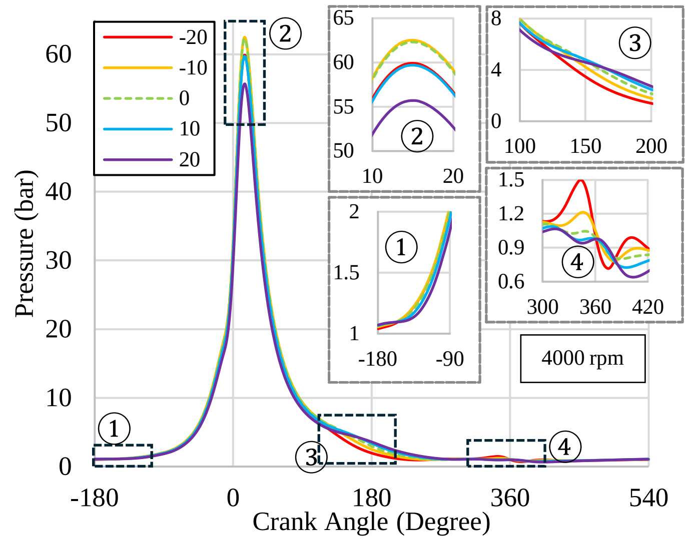

Figure 5. In-cylinder pressure for medium engine speed

In Figure 6, the in-cylinder pressure values at high engine speed (7000 rpm) are presented.

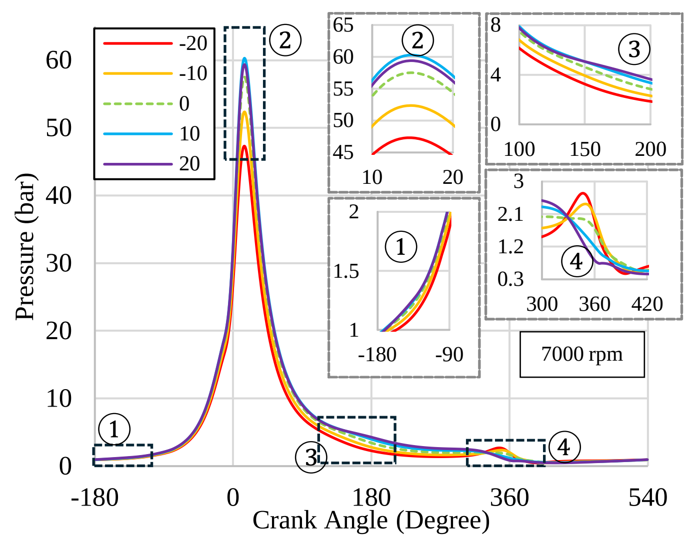

Figure 6. In-cylinder pressure for high engine speed

When Inset graph ① is examined, when the misalignment decreases, the intake valve closes early and therefore the compression process starts earlier. However, the in-cylinder pressure is lower. The possible reason for this is high pressure at high engine speed. volumetric efficiency decreases due to the flow requirement and the shortening of the time used to fill the fresh filler into the cylinder. When Inset graph ② is examined, when misalignment decreases, the maximum in-cylinder pressure e decreases significantly due to the decrease in volumetric efficiency. The highest in-cylinder pressure misalignment is −10 case. In Inset graph ③, when the misalignment decreases, the in-cylinder pressure decreases faster because the exhaust valve opens earlier. In Inset graph ④, when the misalignment decreases, the valve lapping also occurs earlier. However, the pressure fluctuation increases due to misalignment. For example When the sample value is −20, the pressure change in the valve overlap is seen to be in the range of 0.6-2.5 bar.

3.2. General Performance Results

Braking torque, pumping torque, specific fuel consumption, residual gas rate, and volumetric efficiency were examined as performance parameters.

The performance map for brake torque is presented in Figure 7. Especially at medium engine speeds, creating negative misalignment significantly increases the braking torque. On the other hand, in negative misalignment at high engine speeds, engine torque decreases. Braking torque also tends to decrease in positive misalignment. Maximum engine torque occurs at medium engine speed in case of −20 to 5 misalignment.

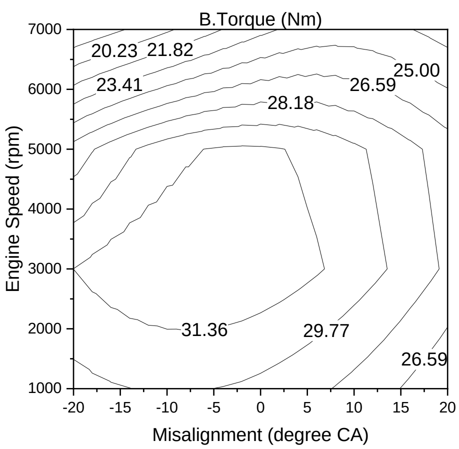

Figure 7. Performance map for brake torque

Figure 8 shows the performance map for pumping torque. As it is known, the main function of the valves is to manage the breathing of the engine and this process results in loss of pumping.

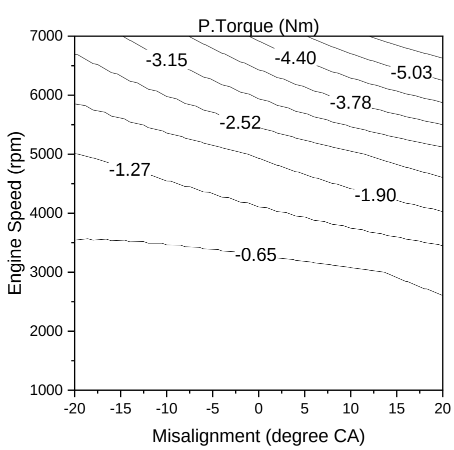

Figure 8. Performance map for pumping torque

Pumping loss tends to increase as engine speed increases. However, especially at high speeds, negative misalignment reduces the pumping torque. Late closing of the valve (positive misalignment) causes the pumping torque to increase. While the pumping torque was −0.65 Nm at low engine speeds, this value was determined as -3.15 Nm to 5.04 Nm at high engine speeds, depending on the misalignment condition.

The expression of engine efficiency based on fuel consumption and brake power is brake specific fuel consumption. Figure 9 shows the performance map for brake specific fuel consumption (BSFC). Whether it is positive misalignment or negative misalignment, BSFC tends to increase in both cases. However, it appears that negative misalignment at medium speeds does not have a significant effect on BSFC. It is seen that BSFC is at the level of 0.25 kg/kWh at low engine speeds. However, it increases up to 0.32 kg/kWh at high engine speeds.

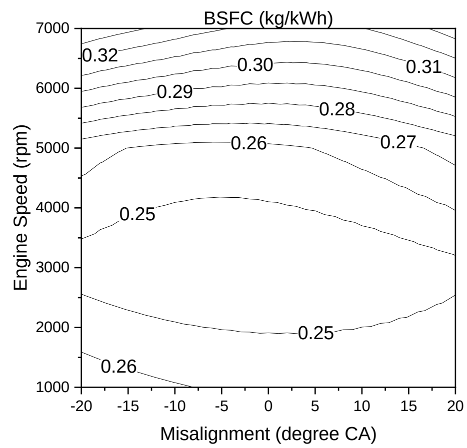

Figure 9. Performance map for brake specific fuel consumption

The operation of the valve system also affects the residual gas fraction (RGF). Figure 10 shows the performance map for RGF. At low and medium engine speeds, negative misalignment or positive misalignment always increases RGF. However, at high speeds, positive misalignment appears to have a reducing effect on RGF.

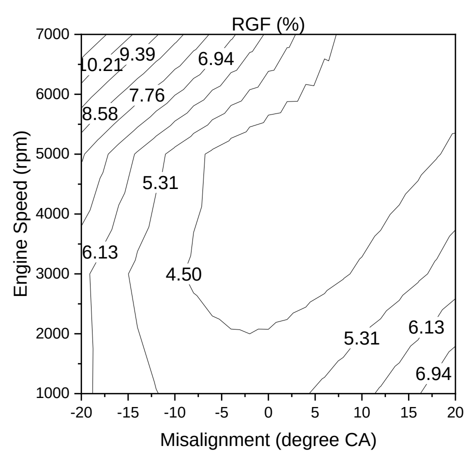

Figure 10. Performance map for residual gas fraction

The main performance of the valve system can be considered as volumetric efficiency. The performance map for volumetric efficiency is presented in Figure 11. Volumetric efficiency is higher, especially for medium engine speeds. When there is positive misalignment or negative misalignment in the engine, volumetric efficiency decreases. Especially at high engine speeds, negative misalignment reduces volumetric efficiency. The highest volumetric efficiency was 0.89 at medium engine speeds. Volumetric efficiency decreases up to 0.70 due to misalignment.

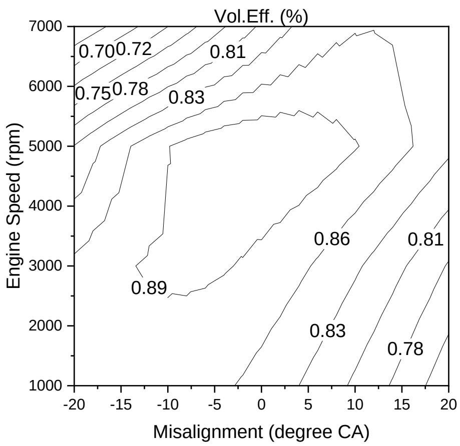

Figure 11. Performance map for volumetric efficiency

3.3. Discussion

According to the results obtained, negative alignment may be necessary at low engine speeds and positive alignment may be necessary at high engine speeds. The use of variable valve timing (VVT), one of today's technologies, can meet this need during engine operation. As it is known, the main goal of VVT is to ensure engine performance and economy by increasing the volumetric efficiency of the engine. Since fixed valve timing is used in conventional engines, engine performance cannot be the same for every engine operating condition. In this study, analysis was performed with the assumption that valve timing misalignment was caused by faulty assembly. As a result of this analysis, reference valve timing gives very good results with the design speed of the engine. In case of a possible valve timing error, performance losses may occur.

4. Conclusions

In this study, a simple simulation model was created for valve timing misalignment, which is an assembly defect in the engine. For example, the opening angles of the valves have been changed from +20 degrees to −20 degrees compared to the normal opening angles. The engine performance resulting from this advanced and retarded valve timing was examined for a four-stroke, spark ignition, single-cylinder engine with an engine volume of 393 cc. In this study conducted for the 1000-7000 rpm engine speed range, first the in-cylinder pressure data were examined in detail and then the general engine performance parameters were examined. Accordingly, opening the valves earlier than necessary at low and medium engine speeds increases the maximum in-cylinder pressure, and at high engine speeds, it reduces the maximum in-cylinder pressure due to the excessive decrease in volumetric efficiency. Regardless of whether the misalignment is positive or negative, pressure fluctuations increase during the valve lapping process. Maximum braking torque occurs at medium engine speeds. Positive misalignment reduces braking torque, especially for low and high engine speeds. However, especially at high speeds, negative misalignment reduces the pumping torque. Whether it is positive misalignment or negative misalignment, BSFC tends to increase in both cases. However, it appears that negative misalignment at medium speeds does not have a significant effect on BSFC. At low and medium engine speeds, negative misalignment or positive misalignment always increases RGF. However, at high speeds, positive misalignment appears to have a reducing effect on RGF. Whether misalignment is positive or negative, volumetric efficiency decreases. Especially at high engine speeds, negative misalignment reduces volumetric efficiency. As a result of the study, it was seen that misalignment negatively affected engine performance. However, it is seen that the value accepted as reference is the optimum value for the operating speed range of the engine. With this study, it has been understood that valve timing, as well as valve system design, is vital for engine performance. The results obtained are of particular interest to engine designers.

Acknowledgment

This article was created using Şule Öztürk's master's thesis titled **“**Effects of valve motion characteristics on performance in spark ignition engine”.

Nomenclature

1D	One dimensional
3D	Three dimensional
BDC	Bottom dead center
BSFC	Brake specific fuel consumption (kg/kWh)
CA	Crank angle (degree)
EPD	Exhaust process duration (°CA)
EVC	Exhaust valve closing (°CA)
EVO	Exhaust valve opening (°CA)
IMEP	Indicated mean effective pressure
IPD	Intake process duration (°CA)
IVC	Intake valve closing (°CA)
IVO	Intake valve opening (°CA)
RGF	Residual gas fraction (%)
RON	Research octane number
TDC	Top dead center
VVT	Variable valve timing
x	Misalignment (°CA)

Conflict of Interest Statement

The authors declare that there is no conflict of interest in the study.

CRediT Author Statement

Emre Arabacı: Conceptualization, Writing-original draft, Validation, Supervision, **Şule Öztürk:** Conceptualization, Methodology, Writing-original draft, software, **Serdar Halis:** Conceptualization, Data curation, Formal analysis

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