The Journal of Engine Research, Vol. 65 (Winter 2022), pp. 03-20

The Journal of Engine Research

Journal Homepage: www.engineresearch.ir

DOI:10.22034/ER.2022.697903

The Effect of Injection Timing and Phasing on the Emission of a Gasoline Single Cylinder Engine

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ARTICLE INFO

Article history:
Received: 1 August 2021
Accepted: 19 March 2022

Keywords:
Single cylinder engine
Fuel phase detection
Injection timing
Four-Stroke engine
Engine emission control

ABSTRACT

Performance evaluation of Internal Combustion Engines (ICEs) and setting different emission standards has manifested the importance of pollution reduction as well as the optimal fuel consumption of these engines. Accordingly, the Engine Management Systems (EMS) are utilized which resulted in optimizing the power alongside the decrease in pollutant emission, through preparing the appropriate air-fuel mixture. Engine management systems are nowadays able to provide an accurate air-fuel mixture. However, the performance of Port Fuel Injection (PFI) engines is also highly dependent on the time of fueling operation which is called the fuel injection phase. There are several methods to achieve the fuel injection phase, the most common of which is using the camshaft position sensor. Nevertheless, this issue is still considered as one of the challenges, devoting much of the researchers' work, in that using camshaft position sensors and similar ones result in increased production costs as well as some complexities in after-sales services. Therefore, this study aimed to design a control algorithm and determine the fuel injection phase as well as identify the moment of inlet valve closure by evaluation of manifold pressure sensor signal of a single-cylinder engine. In the next step, this feature was added to the engine management system and the engine performance was assessed. The results indicated that it is perfectly possible to determine the injection phase through this method. Moreover, to define the effect of this algorithm on emission reduction, the ECE-R40 emission test was held and its results were compared with the emissions level when the engine management system was not equipped with this algorithm. This comparison shows, by using the phase-detection algorithm, the mean carbon monoxide, unburned hydrocarbons, and nitrogen oxides reduced each by 5.9%, 9.4%, and 2.6%, respectively.

1) Introduction

The importance of forming the proper fuel-air mixture in PFI engines and its significant impact on the emission performance and pollutants has prompted many researchers to provide a solution to optimally perform this process through examining various factors. Anand et al. focused on the process of fuel-air mixture preparation at the inlet manifold of a small 4-stroke internal combustion engine. They investigated two-phase fluid modeling, by which the performance of PFI engines is highly dependent on the performance and parameters of the fueling system, and then evaluated the behavior and characteristics of injectable fuel at full load and half load conditions at 3000 rpm rotation for a low-pressure injector system. The results indicated that a large portion of the fuel will accumulate on the wall if the injection fuel is directed on the manifold wall and form fuel film. Despite the high speed of suction at the valve opening, the fuel film formed on the wall is still considerable. However, increasing the temperature of the inlet manifold could prevent forming the fuel film and, in this condition, the amount of fuel remaining inside the manifold is negligible. In addition, operating the fueling when the inlet valve is open and directing the injected fuel into the back of the inlet valve, not only improves the fuel distribution inside the cylinder but also reduces the accumulation on the manifold wall significantly [1].

Similarly, Movahednejad et al. conducted research and used an unstable one-dimensional, multi-phase model to study the mixture preparation process in an indirect injection gasoline engine. Further, they used experimental procedures to survey the fracture mechanism and the fuel spray specifications for conventional multi-hole injectors used in the engine. They expressed, distributing optimal fuel in the interior of the manifold, which is influenced by the spray pattern and manifold geometry, plays a significant role in reducing the fuel clash with the manifold's wall and preventing fuel film accumulation. This action is leading to an improvement in motor performance in transient conditions, as well as reducing unburned hydrocarbons [2]. The above-mentioned issue, along with its impact on the performance and emission pollutants were also studied by researchers in different ways.

For example, Arcoumanis et al. performed empirical tests to obtain information on flow turbulence, fuel droplet size, and its distribution speed for 17.5 and 24 air-fuel ratios at various times in both open and closed valves on a single-cylinder engine, four valves, gasoline spark ignition with a transparent cylinder through various instruments such as doppler laser speedometer. The results of the mixture distribution process with the two implemented strategies (open and closed injection valve) confirmed its correlation with flame images, pressure analysis as well as emission pollutants and the combined benefits of fuel injection during opened valve along with the turbulence and rotation on the more favorable and stable performance of the engine, even with leaner air-fuel ratios through mixed layering and increased flame speed [3].

In addition, Meyer and Haywood concluded that entering the fuel into the cylinder as the liquid is the most important source of the production of unburned hydrocarbons (HC) in the exhaust emission gases, and this process significantly increases engine pollutants during starting and warming up. For this purpose, they evaluated the effect of different parameters of the engine, injector, and fuel on the form of fuel entering into the cylinder. These parameters included fuel injection time, valve timing, injector type, fuel injection geometry, fuel flow fluctuations, and fuel injection directing at the inlet port, the effect of which on the characteristics of inlet fuel droplets (size and velocity) in the surrounding air valve. It is worth noting that these cases were repeated in both open and closed valve openings. The results indicated that mentioned items can differentially affect the fuel droplet characteristics such as size, distribution process in space, and amount of liquid fuel entering the engine during the start and warming up conditions. They expressed the injector type and fuel injection geometry have more effect on the form of fuel entering the cylinder than the other parameters. Yet, injecting the fuel into the inlet valve under open valve conditions results in the highest drop fracture rate [4].

Abdi and Bashi investigated the impact of changing the injection initiation angle on the balance ratio, carbon monoxide, released thermal energy, and ignition delay. During the evaluation, the engine speed, throttle angle, and fuel injection duration were kept constant and the only variable parameter was the initiation angle of injection. They realized, in addition to the overall richness of the mixture, the ignition delay depends on the richness of the mixture around the spark plug, and the richer the mixture around the spark plug, the faster the flame progresses. Therefore, this is achieved through aligning the final moment of the fuel injection with the closing time of the inlet valve and better engine running cold conditions e.g. shorter cranking time. On the other hand, injecting the required fuel during the intake course results in its suction with inlet air into the cylinder, leading to better mixing of the fuel-air mixture and reducing carbon monoxide pollutants [5].

Further, if the fuel injection operations are conducted in each crankshaft rotation, the low temperature of the manifold in cold conditions results in distilling the fuel due to its impact on the wall, which is collected in the back of the valve as the liquid, leading to entering liquid fuel into the engine and increasing unburned hydrocarbons (HC), as well as a lack of proper engine acceleration in transient conditions [6].

Surveying other studies on the fuel injection process in PFI engines indicates that sequential fuel injection and its synchronization with the intake course have many advantages, above all, the engine's capability of operating with a leaner fuel-air mixture as well as producing fewer exhaust emissions [7, 8].

Therefore, various solutions such as implementing camshaft position sensor are used in this type of engine through which the fuel injection operations can be managed sequentially due to the use of sensors and the required electronic components in the hardware part of the engine management unit, which results in increasing the production costs as well as the complexity of engine repair in the after-sales service sector. On the other hand, there is no control over the injection phase within the injector systems used in motorcycles with engine volume less than 250 cc to reduce production costs which bring with the above-mentioned complexities. To achieve this aim, a large number of researchers have attempted to provide the fuel injection phase control capability in such motors through using innovative methods.

Galtier and Zhang [9] reported that suction operations on the engine have a direct impact on the air pressure inside the inlet manifold by developing a method and apparatus capable of detecting the phase position into the internal combustion engines without using the additional sensors. In this method, the phase positioning is identified through recognizing pressure drop during opening the inlet valve as well as its increase during closing the valve and applying a correction coefficient as a function of variable operating load and rotational speed of the motor. Similarly, Schwulst and Pattantyus [10] indicated that the engine control unit is required to identify the crankshaft position and the phase of the internal combustion engine by examining and displaying the fluctuations of the inlet air pressure signal. In this invention, since the valves mechanism is mechanically attached to a particular position of the crankshaft, the control unit detects the crankshaft position and simultaneously engine working cycle through examining the fluctuations in the signal of the air pressure sensor during suction. Further, the control panel can calculate the crankshaft rotational speed and its position and determine the start of the fuel injection and the timing of the ignition. On the other hand, the motor can be equipped with a crankshaft position sensor to increase the accuracy of system performance.

David G. McKendry et al. [11] could detect the exact angle of the crankshaft through the manifold pressure sensor information at a specified point. Therefore, the crankshaft angle can be identified by setting the cylinder by default and matching the part of the pressure sensor signal, which is most affected by the suction course. Since the maximum pressure drops inside the manifold occur in the suction course, it is possible to determine the suction course of a specific cylinder of the engine. The mentioned cases are for internal combustion engines used in cars with multiple cylinders. These engines have a significant difference from small single-cylinder engines used in motorcycles. For example, the maximum speed of these engines reaches 6000 rpm, while it is around 14000 to 12000 rpm for the motorcycles. On the other hand, the speed changes and rotational speed in such engines are very fast due to the low inertia of the crankshaft, which causes turbulence in the airflow into the engine [12].

Based on the results, it is easy to understand the need to control the emission pollutants from the performance of internal combustion engines. Therefore, this study aimed to investigate the effect of phase-detection and instantaneous end-of-burn control on exhaust emissions of small petrol single-cylinder engines used in the motorcycles. In this article, a new method is used to detect the phase of the injection and control the moment at which the fueling should finish, according to the manifold pressure sensor and engine speed data. Implementing this method both prevents increasing production costs and provides some benefits such as fuel injection time management to avoid its accumulation at the inlet manifold. Then, the effect of implementing this method on changing the engine emission pollutants based on ECE-R40 emission assessment cycle is discussed.

2) Methods

The design of the intake manifold in a single-cylinder engine has some significant differences from the intake manifold used in multi-cylinder vehicle engines due to some limitations such as lack of proper space. For example, the plenum chamber, embedded in the engine air intake path between the throttle body and the air intake port inside the cylinder head, is removed due to limited space, which reduces the ratio of input manifold volume to the cylinder displacement volume. On the other hand, the area of the air intake path into the cylinder, which is provided by opening the inlet valve, is relatively small compared to the volume of the combustion chamber. These factors increase the dependence of pressure changes inside the intake manifold on the engine speed and the crankshaft angle and also cause the inlet manifold and cylinder to reach thermodynamic equilibrium in a very short time [12]. Therefore, the inlet air dynamics can be mathematically modeled by considering the enthalpy equilibrium in the adiabatic subsonic between the outer space and the throttle [12].

$$\frac{1}{2}\left(\frac{v_1}{C_d}\right)^2+\frac{k}{k-1}\frac{P_1}{r_1}=\frac{1}{2}\left(\frac{v_2}{C_d}\right)^2+\frac{k}{k-1}\frac{P_2}{r_2} \quad (1)$$

Then, the relationship between the intake manifold and the throttle surface is defined by the continuity equation as follows:

$$S_1r_1v_1=S_2r_2v_2 \quad (2)$$

On the other hand, the following results were obtained after modeling the adiabatic flow as polytropic:

$$\frac{P_2}{P_1}=\left(\frac{r_2}{r_1}\right)^n \quad (3)$$

In equation (3), n represents the polytropic coefficient, the selection of which as 0, 1, k and ∞ creates different thermodynamic conditions such as constant pressure, constant temperature, etc. The pressure difference results in creating airflows on the engine entry port; however, the speed of this flow cannot exceed the speed of sound. Therefore, when the flow speed is equal to the propagation speed, then the mass flow speed is saturated. Considering $\gamma=P_2/P_1$ and solving the equations (1) to (3), it can be observed that the flow reaches saturation when γ satisfies Equation (4).

$$0=\frac{n-1}{2}\left(\frac{S_2}{S_1}\right)^2\gamma^{1+\frac{1}{n}}-\frac{n+1}{2}\gamma^{1-\frac{1}{n}}+1 \quad (4)$$

Regarding γ^* as the answer to the above equation, γ^* indicates the critical pressure ratio. Therefore, if $\gamma^*<P_2/P_1$, the flow rate is lower than the speed of sound. Otherwise, the flow is saturated. Therefore, supposing $S_2/S_1\approx 0$, γ^* can be calculated as equation (5):

$$\gamma^*\approx\left(\frac{2}{n+1}\right)^{\frac{n}{n-1}} \quad (5)$$

The saturated flow rate can also be calculated by considering $P_s=\gamma^*P_1$ and using equations (1) to (3). In the next step, after entering the air into the inlet manifold, the equilibrium enthalpy equations are defined as follows [12]:

$$\frac{1}{2}{v_2}^2+\frac{k}{k-1}\frac{P_2}{r_2}=\frac{1}{2}{v_3}^2+\frac{k}{k-1}\frac{P_3}{r_3} \quad (6)$$

According to the continuum equation, we have:

$$\frac{d}{d_t}(V_3r_3)=S_3r_3v_3=S_2r_2v_2 \quad (7)$$

where V_3 represents the volume of the stagnation region. Because the reciprocating movement of the piston inside the cylinder in the suction course makes the energy changes in the manifold relaxation chamber and the rate of energy changes in this environment is equal to the enthalpy of passing current per unit time. Then, the rate of energy changes in this range can be calculated through Equation (8):

$$\frac{d}{dt}\left(\frac{1}{k-1}P_3V_3\right)+\frac{dW}{dt}=\left(\frac{1}{2}v_2^2+\frac{k}{k-1}\frac{P_2}{r_2}\right)S_2r_2v_2 \quad (8)$$

However, it is worth mentioning that the solution obtained from Equations (7) and (8) is not correct to calculate the energy of the saturated flow because the mass flow rate, in this case, has nothing to do with P_2 and r_2. Conversely, the values of P_s, r_s and v_s should be replaced by P_2, r_2 and v_2, respectively, to calculate the rate of energy changes through Equations (7-8) in saturation state through the mass and energy conservation theorems in saturation. On the other hand, it is necessary to determine the equations for the piston movement within the cylinder and the timing of the valves, and their relationship to the changes in the manifold pressure because the pressure changes inside the manifold are strongly dependent on piston movement and timing of valves. Therefore, the position and velocity of the piston inside the cylinder can be obtained based on Equations (9) and (10).

$$x = l_c\left(1-\sqrt{1-\frac{l_s^2}{4l_c^2}sin^2\,\theta}\right)+\frac{l_s}{2}(1-cos\,\theta) \tag{9}$$

$$\frac{dx}{dt}=\frac{d\theta}{dt}\left(\frac{l_s^2}{4l_c}\frac{cos\,\theta}{\sqrt{1-\frac{l_s^2}{4l_c^2}\,sin^2\,\theta}}+\frac{l_s}{2}\right)sin\,\theta \tag{10}$$

On the other hand, regarding P_3, r_3, and V_3 as manifold pressures, density, and volume at the time precisely before the valve opening moment and also assuming that P_4, r_4 and V_4 represent pressure, density, and volume inside the cylinder, respectively, if the inlet manifold and space inside the cylinder reach a thermodynamic equilibrium at the time the valve is open, we will have:

$$P_m=\frac{P_3V_3+P_4V_4}{V_3+V_4} \tag{11}$$

$$r_m=\frac{r_3V_3+r_4V_4}{V_3+V_4} \tag{12}$$

$$V_m=V_3+V_4 \tag{13}$$

It is worth noting that the index m is used to introduce the manifold and cylinder space seamlessly while opening the inlet valve. The assumption that the space inside the cylinder and the manifold are integrated when the inlet valve in the motorcycle is open is considered by the structural characteristics of this group of engines. One of these features is the low ratio of the volume of the manifold to the volume created in the suction course, which causes the complete evacuation of the air inside the manifold into the cylinder. Also, due to the high ratio between the air inlet surface and the volume of the combustion chamber, this integrated space is balanced before the outlet valve is closed. The volume of integrated space can be calculated by introducing the inside of the cylinder and the volume of the combustion chamber:

$$V_m=V_3+V_{TDC}+S_4x \tag{14}$$

Therefore, if the speed of transmission is less than the speed of sound, we have:

$$\frac{1}{2}\left(\frac{v_1}{C}\right)^2+\frac{k}{k-1}\frac{P_1}{r_1}=\frac{1}{2}\left(\frac{v_2}{C}\right)^2+\frac{k}{k-1}\frac{P_2}{r_2} \tag{15}$$

$$S_1r_1v_1=S_2r_2v_2 \tag{16}$$

$$\frac{P_2}{P_1}=\left(\frac{r_2}{r_1}\right)^n \tag{17}$$

$$\frac{1}{2}{v_2}^2+\frac{k}{k-1}\frac{P_2}{r_2}=\frac{1}{2}{v_m}^2+\frac{k}{k-1}\frac{P_m}{r_m} \tag{18}$$

$$\frac{d}{d_t}(V_mr_m)=S_3r_mv_m=S_2r_2v_2 \tag{19}$$

$$\frac{d}{dt}\left(\frac{1}{k-1}P_mV_m\right)+P_m\frac{dV_m}{dt}=\left(\frac{1}{2}v_2^2+\frac{k}{k-1}\frac{P_2}{r_2}\right)S_2r_2v_2 \tag{20}$$

In addition, we have the following equation when the current is saturated:

$$\frac{1}{2}\left(\frac{v_1}{C}\right)^2+\frac{k}{k-1}\frac{P_1}{r_1}=\frac{1}{2}\left(\frac{v_s}{C}\right)^2+\frac{k}{k-1}\frac{P_s}{r_s} \tag{21}$$

$$S_1r_1v_1=S_2r_sv_s \tag{22}$$

$$\frac{P_s}{P_1}=\left(\frac{r_s}{r_1}\right)^n \tag{23}$$

$$P_s=\gamma^*P_1 \tag{24}$$

$$\frac{d}{d_t}(V_mr_m)=S_2r_2v_2 \tag{25}$$

$$\frac{d}{dt}\left(\frac{1}{k-1}P_mV_m\right)+P_m\frac{dV_m}{dt}=\left(\frac{1}{2}v_s^2+\frac{k}{k-1}\frac{P_s}{r_s}\right)S_2r_sv_s \tag{26}$$

On the other hand, inlet airflow results in oscillation and pulse motion due to the factors such as blows from opening and closing of valves, the resonance of air inlet, etc., which is necessary to be considered in the calculation process. This process can be modeled as a damped oscillatory signal. Its distance can be calculated by the speed of sound and the distance between the air filter and the inlet valve, and its amplitude can be calculated as a proportion of the mass flow in the last cycle. In addition, its damping time constant depends on the viscosity of the air. Then, we have:

$$P_p=A_pe^{-\frac{t-t_{IVC}}{\tau_p}}\,sin\left[\omega_p(t-t_{IVC})+\theta_p\right] \tag{27}$$

By solving the equation (27), according to the explanations given concerning the inlet airflow, which was discussed in the preceding sections, and placing it in the process of calculating the manifold pressure, the following relations will be obtained, in which $\hat{P}_3$ is the matching pressure and $\hat{P}_m$ is the estimated pressure inside the air manifold [12]:

$$\hat{P}_3 = P_3 + P_P \quad (28)$$

$$\hat{P}_m = P_m + P_P \quad (29)$$

The process of air pressure changes inside the manifold can be observed by solving the above equations. Figure 1 displays the graphical representation of the continuous solution of these equations.

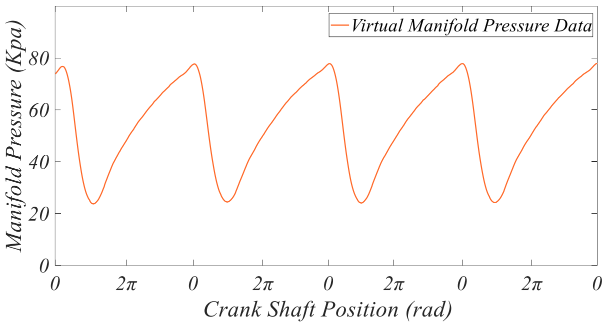

Figure 1: Manifold pressure signal

As shown, the trend of changes in air pressure inside the manifold is observed well. Manifold pressure signal experiences more sudden changes due to opening and closing of the air valve and transient piston movement in single-cylinder engines because of the simple structure of the inlet manifold and the absence of a relaxation chamber [12].

On the other hand, the manifold pressure sensor data input and inlet manifold pressure changes were measured to evaluate the accuracy of the manifold pressure virtual signal obtained by modeling the inlet air to the motor. At this stage, the High-Speed Data Acquisition (AI6C) and data storage at the rate of 100 kHz were used simultaneously in six separated channels to receive and store the pressure sensor signal. Figure 2 shows the signal received from the manifold pressure sensor.

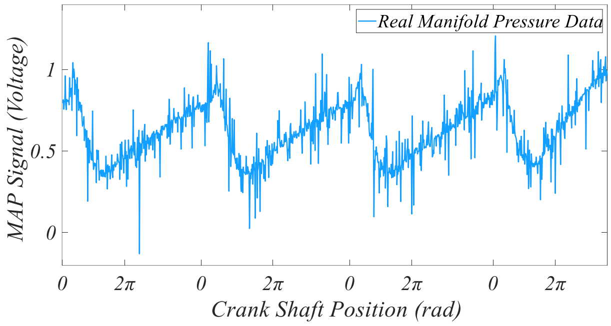

Figure 2: Manifold pressure sensor signal

As shown, the general trend of changes in the information obtained from the manifold pressure sensor is in line with Figure 1, where the increasing trend of the signal indicates an increase in air pressure in the inlet manifold and its reduction indicates a pressure drop. As displayed in Figure 2, the received manifold pressure sensor signal has many momentum fluctuations due to different noises which make it difficult to accurately calculate intra-manifold pressure.

Therefore, it is necessary to identify the appropriate frequency of data acquisition because high-speed data acquisition increases the stored data volume and reduces data processing speed. Further, low-speed data acquisition eliminates the ability to retrieve the received signal properly. Therefore, it is necessary to identify the maximum frequency of this signal for proper frequency recording. Thus, the Fast Fourier Transform (FFT) was used to detect the maximum frequency of this signal according to the relation (30).

$$X(f) = \int_{-\infty}^{+\infty} x(t)\, e^{-j\omega t}\, dt \quad when \quad \omega = 2\pi f \quad (30)$$

After performing the above operation on the received signal using MATLAB Software, the maximum frequency of the manifold pressure signal was calculated to be about 200Hz, as shown in Figure 3.

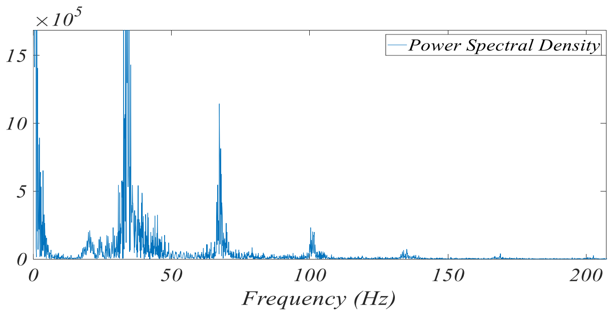

Figure 3: Maximum signal frequencies received from the manifold pressure sensor

According to Nyquist Sampling Theorem, the data acquisition frequency should be at least 2 times greater than the maximum frequency in the signal [13].

$$f_s \geq 2 f_c \quad (31)$$

Such things as increasing the amount of received data, decreasing processing speed, as well as the likelihood of losing essential data for signal recovery can be easily prevented by this method. Therefore, data acquisition with a 1 kHz frequency was included in our working schedule.

Filtering the received signal

Opening and closing the engine inlet valve at various times result in making some changes in the signal received from the pressure sensor, which is visible as an increasing or decreasing trend. Therefore, the overall trend of signal changes received by the sensor according to the crankshaft angle can be fully followed, which is a useful issue. On the other hand, the existing and effective noise on the signal is in such a way that it can merely increase or decrease the instantaneous amount of signal, without affecting its overall trend (Figure 2).

However, this sudden increase or decrease of the signal caused by different noises can have a detrimental effect on calculating the mass of the inlet air inside the cylinder. Therefore, unnecessary noise and oscillations of this signal were filtered and eliminated. In this regard, several different filters were used to eliminate the noise in the signal. These filters included root mean square filter, moving average filter, and Finite Impulse Response, the results of which are shown in Figure 4.

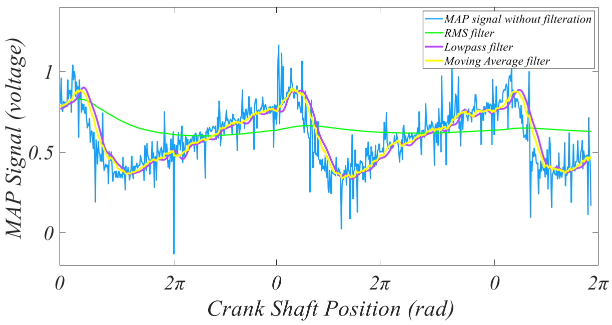

Figure 4: Results of applying different filters

As shown in Figure 4, the root means square filter changes the overall signal trend. Thus, it is not considered an optimal filter. However, using the low-pass filter and the moving average preserves the overall signal trend. In addition, the low pass filter has a higher power to eliminate the noise, despite using this filter increasing the latency of calculating the manifold pressure. Therefore, the moving average filter was used to improve the received signal. This filter is the most commonly used one in digital signal processing due to its simplicity [14]. Further, this filter itself is a simple example of a low-pass FIR filter that generates an output signal by averaging M data from the input signal, which is in line with the equation (32) [15].

$$y\,[i] = \frac{1}{M} \sum_{j=0}^{M-1} x\,[i+j] \quad (32)$$

First, it seems that the moving average filter is not working properly due to its simplicity. However not only is this filter suitable to be used in various parts, but also it is an optimal filter for eliminating sudden noise while keeping the main signal change process. 10 samples, 15 samples, and 20 samples in the first, second, and final stages, respectively were chosen and evaluated for sampling to examine the performance of this filter in removing existing noise, the results of which are shown in Figure 5.

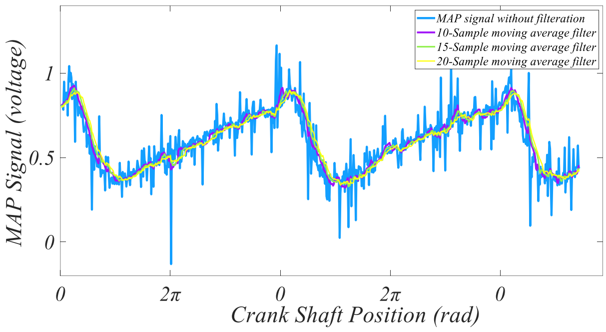

Figure 5: Results of applying moving average filters with different samples

As shown, the signal from the pressure sensor is displayed in blue before performing the filtering operation. In addition, the signals obtained from filtering operations with 10, 15, and 20 numerical samples are displayed in purple, green, and yellow, respectively. Based on the variations of all the signals, in addition to maintaining the overall signal changes trends, it eliminated the sudden noise and the desired signal can be observed at the output. In addition, as shown in Figure 5 the best result is achieved through the previous 20 samples to determine the output signal and independence from the number of samples is confirmed.

Control algorithm

Since the present study aimed to determine the fuel dispersion phase based on the manifold pressure sensor and the engine speed, it is necessary to carefully evaluate the signal changes process of these sensors and their relationships. The design of the valve mechanism in the used engine is in such a way that the inlet valve opens 22 degrees before the piston reaches the top dead center due to an increase in the time of intake course and the volume efficiency. At this time, the signal from the pressure sensor changes abruptly, indicating the start of the intake course. Under these conditions, because of the upward movement of the piston, the pressure inside the manifold increases momentarily, which is manifested as backpressure and continues until the piston can reach Top Dead Center (TDC). Then, as the piston moves downward, the inlet manifold pressure drops and the output signal of this sensor shows a decreasing trend. Following this process, the inlet valve closes 40 degrees after the piston passes through the bottom dead center and the intake course stops. It is worth noting that according to the experiments, the manifold pressure sensor has a time delay of 1.2 milliseconds. The trend of changes in the manifold pressure sensor signal and its relation to the signal received from the engine speed sensor is displayed in Figure 6.

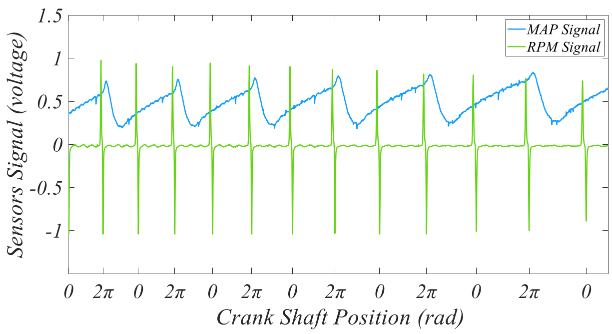

Figure 6: Manifold pressure sensor signal changes based on the motor speed sensor signal

After identifying the relationship between the change trends in the manifold pressure sensor and the engine speed sensor data, the flowchart control algorithm was prepared to determine the fuel injection spray phase. Figure 7 displays the flowchart of the program in question.

As displayed in Figure 7, the first step is to examine the signals received by the sensors. Second, the base tooth position installed on the crankshaft is examined to detect the TDC, which the manifold pressure signal is evaluated if the data related to the base tooth is identified properly. Because in this kind of engine, the flywheel has only one tooth and the engine speed sensor just sends a signal to the engine control unit while passing through it, the mean pressure value (mean M data used in the filtering operation) at the time of receiving the engine sensor data while closing the inlet valve (Index A in Figure 8) is different from the mean pressure value while opening the inlet valve (Index B).

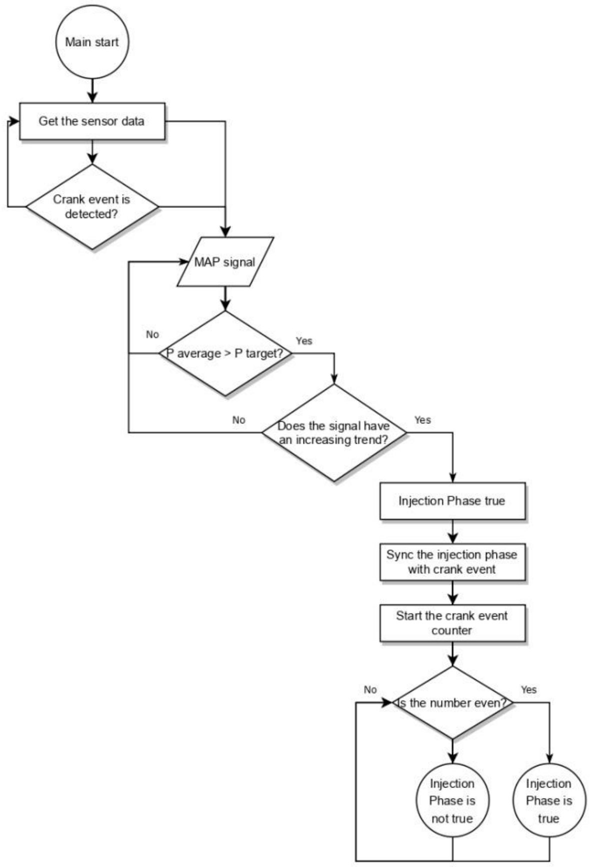

Figure 7: Flowchart of the fuel phase detection algorithm

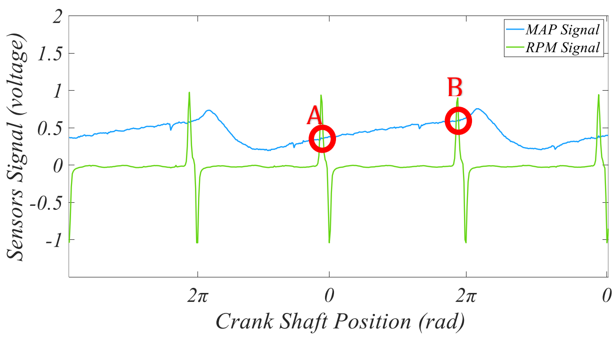

Figure 8: Displaying the manifold mean pressure difference when closing and opening the inlet valve

Therefore, the difference in these two states is considered as the default range in the control algorithm, and the calculated mean pressure based on the sensor data should be greater than that of the default range and the trend should be incremental to detect the fuel injection phase.

$$if\ \frac{P_{i+1} - P_i}{t_{i+1} - t_i} > P_{target} \tag{33}$$

$$if\ P_{target} > 0 \tag{34}$$

$$then\ injection\ phase = true \tag{35}$$

In such a situation, it is easy to identify the fuel injection phase in the idle cycle and issue an order confirming the accuracy of the fuel injection phase. However, if the engine speed is high, the pressure changes inside the manifold are very limited due to the opened throttle, and no significant pressure difference is observed when receiving the engine torque signal before starting the suction course and its starting moment. Therefore, based on the flowchart, if the fuel injection phase is correctly detected at a slow speed, the instruction is synchronized with the signal received from the engine sensor of the motor.

In these motors, the motorcycle electric throttle is designed to have only a base tooth. Therefore, the fuel injection phase can be accurately identified through synchronizing the identified fuel injection phase, as well as enumerating the passing teeth in front of the motor engine sensors in even and odd. This technique contributes to the elimination of the problems of identifying the fuel injection phase at high speeds, which can be detected well under all conditions. Based on the above-mentioned issues, the volumetric efficiency increases, and the combustion quality improves if the fuel injection operation is single-injection and is performed at the optimum time proportional to the inlet valve openness, leading to a decrease in emission pollutants [5,6].

As a result, the fuel injection operation can be initiated in such a way that the moment of termination can coincide with the inlet valve closure moment or whenever from the intake course through identifying the moment of the inlet valve closure according to the motor information, as well as the fuel injection phase information due to the constant timing of the valves mechanically. For example, this important issue can be achieved by stabilizing the ending moment of the fuel injection with the ending time of the suction course [5].

In addition, in other conditions where fuel suction along with air into the cylinder leads to a better mixture and reduction in CO carbon monoxide, the fuel injection operation is coordinated with starting the suction course and opening the inlet valve. Therefore, the algorithm for calculating the starting time of the fuel injection operation during the spraying phase is designed according to the inlet valve closing moment (Figure 9).

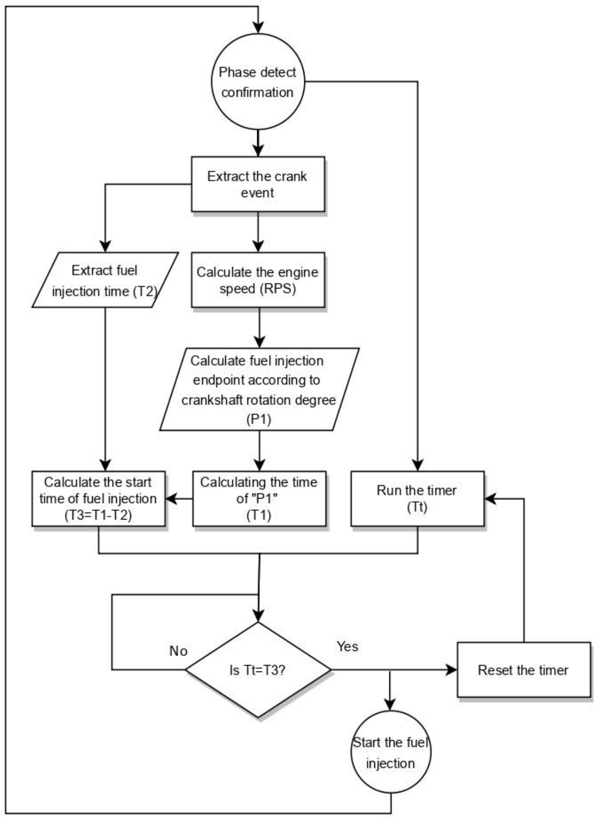

Figure 9: Flowchart for fuel injection operations in the suction course

As shown, the control algorithm performs the timer set-up, calculates the engine speed in speed per second, as well as obtains the final fuel injection time set by fuel control strategies upon the approval of the spraying phase. The endpoint of the fuel injection can vary in different conditions, known as the fuel injection phase table, and is calibrated by the degree of crankshaft angle. This can be the maximum when the inlet valve is closed. Therefore, this amount can coincide with the inlet valve closure, which results in obtaining the related number by the control algorithm and calculating its time. Then, the moment of initiating the fuel injection operation with due attention to the time of receiving the phase approval is determined by subtracting the fuel injection time from the calculated time. Then, the obtained number is compared with the timer output number. If the two numbers are equal (or greater), the fuel injector is activated and the fuel injection operation is initiated.

Simulation

Determining the fuel injection phase

The Simulink_MATLAB Software is used to process the signals received from manifold pressure and engine speed sensors, as well as simulate the control algorithm performance of the fuel injection phase. This is implemented by receiving the signal of the air pressure sensor and the engine speed of the concerned operation. First, the manifold pressure sensor signal is processed and evaluated logically for the mean value and then for the trend of changes, where the true (logical answer) result of this evaluation indicates the correct detection of the fuel injection phase.

However, it is not possible to detect the correct phase according to the sensor information because the manifold pressure sensor signal changes at high speed. Therefore, after identifying the fuel injection phase at the idle speed, its information is synchronized with the engine speed signal and then the phase detection operation is determined in all conditions both idle and high engine speeds according to the engine speed data. This can be precisely performed through this method at high speeds where it is not possible to detect the phase according to the pressure sensor data.

Identifying the moment of the inlet valve closure

As mentioned above, if the fuel injection operation is conducted while the inlet valve is open, it increases the volumetric efficiency and improves the combustion quality as well as reduces the emission pollutants [5,6]. Therefore, starting the fuel injection operation can be conducted as optimally as possible by identifying the moment of the inlet valve closure based on the engine speed data and the fuel injection phase. For example, this important issue can be obtained by stabilizing the ending moment of fuel injection with the ending moment of the suction course when starting the engine in cold conditions where increased fuel richness around the sparking plug improves the engine's ability to turn on [5]. The moment of completing the fuel injection operation is based on the angle of the crankshaft rotation relative to the base point. The default values are first recorded in the fuel injection phase table and then calibrated according to the engine operating conditions. If the moment of completing the fuel injection operation is determined after closing the inlet valve, some of the engine fuel accumulates behind the valve chamber and enters the cylinder in the next cycle. Therefore, to prevent such an issue, the maximum moment of completing the fuel injection operation coincides with closing the inlet valve to prevent occurring such an issue. Hence, the control algorithm is identified at the inlet valve closing moment after receiving the approval of the fuel phase and engine speed signal. It can be done through Equations (36) and (37).

$$t_{IVC} = \frac{60000(\alpha + \beta)}{2\pi N} \quad (36)$$

As shown, the values of α and β are always constant and the engine speed is denoted as N, which is some crankshaft revolutions per minute. Therefore, it is easy to calculate and identify the moment of closing the inlet valve relative to the moment of receiving the engine sensor signal by placing the above values in Equation (36).

Now, if the moment of ending the fuel injection is synchronized with closing the inlet valve, the fuel injection operation initiation can be determined since the moment of the inlet valve closure by subtracting the final fuel injection time, which is the sum of the baseline fuel injection time with the correction coefficients. This is conducted based on Equation (37):

$$IST = T_{IVC} - IT \quad (37)$$

Figure 10 shows the fuel injection operation during the intake stroke graphically.

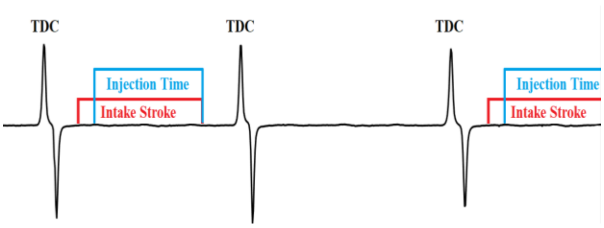

Figure 10: Performing fuel injection operations in the suction course

The control algorithm related to fuel injection operations in the suction course was simulated and evaluated through the Simulink-MATLAB Software as in the previous algorithms.

Pollutant test

Emission pollutants of internal combustion engines include toxic and non-toxic gases, chemical particles, etc. Environmental protection organizations determine the allowed limit of the pollutants emitted from their exhaust and present in the form of permitted emission standards through examining the different conditions and classifying motor vehicles into different groups. Table 1 indicates the pollution standards set for motorcycles with an engine volume of less than 150cc.

Table 1: Pollution standards set for motorcycles with engine volume less than 150cc [16]

	Euro 1	Euro 2	Euro 3	Euro 4	Euro 5
CO (g/km)	13	5.5	2	1.14	1
HC (g/km)	3	1	0.3	0.17	0.1
NO_x (g/km)	0.3	0.3	0.15	0.09	0.06
PM (g/km)	-	-	-	-	0.0045
SHED* test	-	-	-	YES	YES
On-board Diagnostic	-	-	-	YES (OBD1)	YES (OBD2)
Durability	-	-	-	20,000	Lifetime

To measure the emissions and also to evaluate the performance of the motorcycle, the motorcycle was placed on the chassis-dynamometer, the equipment used to test and measure the emissions can be seen in Figure 11.

Figure 11: Chassis-dynamometer and test equipment

In addition, the process of measuring the emission pollutants was following the ECE-R40 cycle, which is shown in Figure 12.

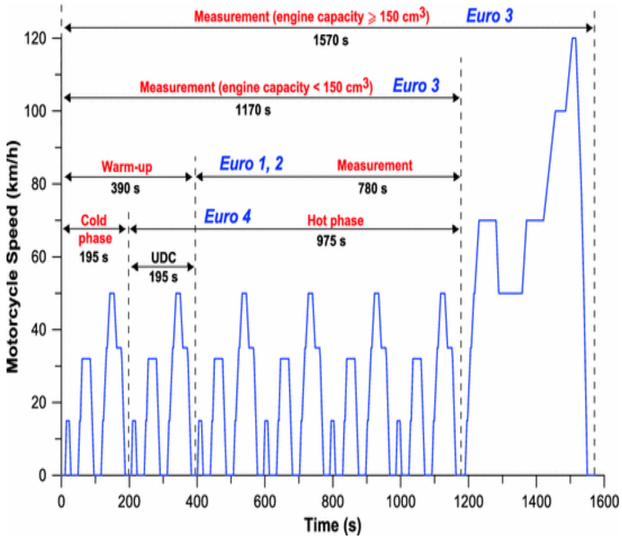

Figure 12: Pollutant test cycle [16]

As can be seen, the ECE-R40 cycle is designed in such a way as to simulate the performance of a motorcycle in real conditions. First, the engine is started and then working in the idle condition for 10-11 seconds. It then starts moving with the first gear and reaches a speed of 15km/h and stabilizes for a while. As illustrated in Figure 12, the velocity change and stabilization process are designed to simulate vehicle performance in both transient and steady states conditions. At different stages, the driver should do the up and down gear shift to track the speed, according to the provided pattern. Table 2 indicates the average speed, maximum speed, and maximum acceleration during this test.

Table 2: Mean speed, maximum speed, and acceleration during the pollution cycle

Average Speed (km/h)	Max Speed (km/s)	Max Acceleration (m/s^2)
18.7	50	1.06

Based on the above-mentioned issue, the impact of applying the fuel-phase control algorithm on pollutants should be evaluated. Therefore, the motorcycle underwent the pollutant test based on the cycle shown in Figure 12. In the first test, the motorcycle system was equipped with an electric fuel injection system and was controlled by the engine management unit. However, the engine management unit lacked the phase-detection control algorithm, and the fuel injection operations were performed at each round of the crankshaft. In the second test, the fuel management system was equipped with the designed algorithm, and the fuel injection operations were performed in a single injection method, during the intake stroke. It is worth noting that the test conditions are based on Table 3 and each test was repeated twice to examine the repeatability of the results.

Table 3: The motorcycle specifications and initial test conditions

Specification of tested motorcycle		
Engine type	Spark Ignition (SI)	
Engine volume	149.4 cc	
Number of cylinders	1	
Number of valves	2	
Max. power (kW)	8.19@8017rpm	
Max. torque (N.m)	10.48@6541rpm	
Piston displacement (mm)	49.5	
Compression ratio	9.5:1	
Engine cooling system	Air-cooling	
Oil temperature at start time (°C)	21	
Fueling system	Carburetor	
	Electric injector	Double injection
		Single injection
Gear No.	5	
Final drive ratio	3.74	

Verification

For validating the information obtained from modeling, simulation, control algorithm design, etc. first, the used model was validated by comparing its results with the data obtained from the data acquisition process. Then, the simulation results and performance of the designed controller were verified by programming the engine management unit, running the engines under different conditions, and observing the signals received from the manifold pressure sensor and fuel injector.

Further, the designed interfaces were used to communicate by computer with the engine management unit. This software enables the user to see the process of changing various engine parameters during engine operation in online and easily changes the numerical values in the Base MAPs such as fuel injection, sparking ignition, the moment at which fuel injection will be completed, and other numeric values in the engine management unit memory. In addition, by using this interface the operator can observe the effects of these changes on the engine power and torque, as well as the emission pollutants. Figure 13 shows the communication software.

Figure 13: Communicating software with the engine management unit

The performed pollution test in this study is another issue where its results should be evaluated. Therefore, the results obtained from the pollution test, when the engine management system was equipped with the designed algorithm, were compared with the results of the pollution test when the engine management system was working without the designed algorithm. In addition, the results were evaluated with the results presented in similar studies, which helps to ensure the verification of the extent and trend of the changes in the emission pollutants.

3) Results

After performing the calculations related to the air dynamics modeling and the input manifold pressure changes, as well as the data processing and signal filtering, received from the manifold pressure sensor, the results are plotted simultaneously in Figure 14.

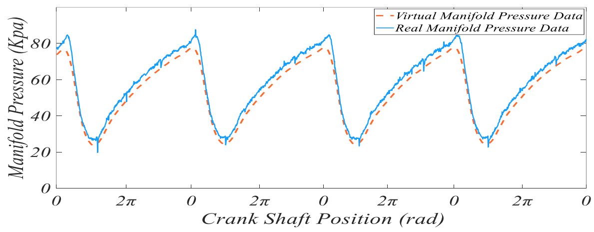

Figure 14: Input manifold pressure changes from modeling and real-time data collection

As shown in Figure 14, the orange diagram shows the process of pressure changes from the modeling, and the blue diagram shows the data

obtained from the pressure sensor in real conditions.
As shown, the result of the modeling which shows the pressure changes inside the manifold is similar to the changes recorded by the pressure sensor mounted on the inlet manifold. The most significant difference between these results is that the model result is at the lower level in comparison with the diagram obtained from the actual data. This difference, known as the error between the model and the actual condition at most is less than 4%, which is negligible. However, the existing error can be reduced by calibrating the model coefficients according to the actual data.
Moreover, Figure 15 shows the results of the controlling algorithm simulation of determining the fuel injection phase through Simulink_MATLAB Software. As shown, the blue signal is related to the Manifold pressure sensor information, the green signal refers to the engine speed sensor information, the black signal is related to the time at which the inlet valve is closed, and the purple signal is considered as the fuel injection time, the final moment of which coincides with the moment of the valve closure.

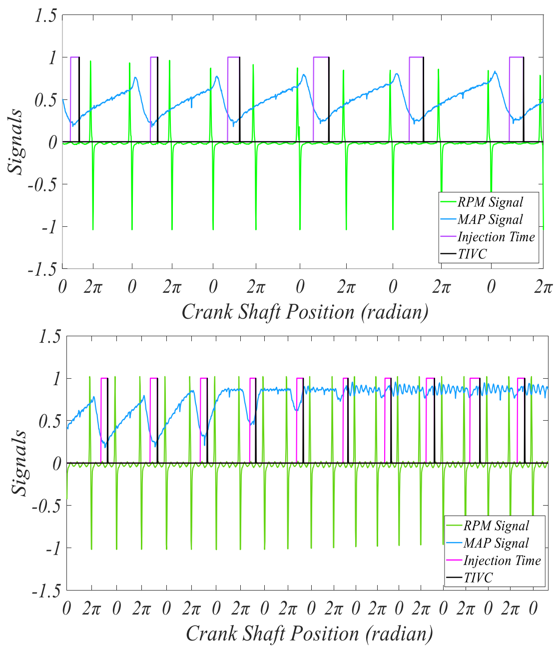

Figure 15: Results from algorithm simulation in the software environment

As shown in Figure 15, the fuel injection phase is well identified in all engine operating conditions including idle, transient as well as high speeds, and the fuel injection is done in a way that completes in coincides with the time of inlet valve closure.
In addition, Figure 16 shows the results of experimental tests which were conducted to verify the performance of the designed controller of phase detection and fuel injection operations during the opening time of the inlet valve. In Figure 16, the yellow signal is related to the manifold pressure sensor information and the blue signal refers to the fuel injection duration.

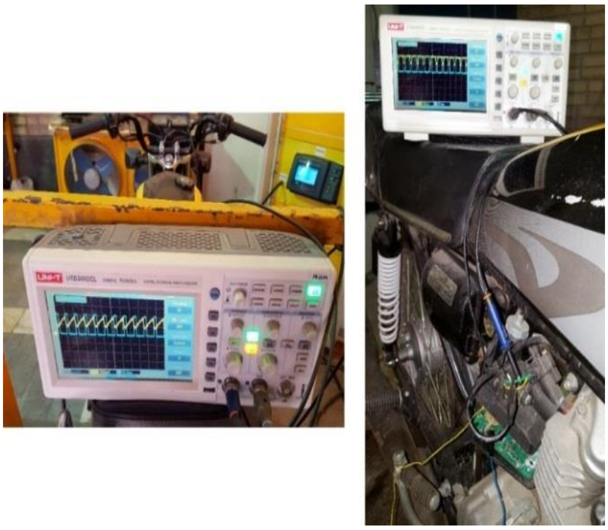
Figure 16: The results of the experimental tests

Results of pollutant test
For examining the change of exhaust emissions, the emission tests were done based on the cycle shown in Figure 12. In the first test, the engine management system was not equipped with the designed algorithm and the fuel injection operation was performed at each revolution of the crankshaft. In the second test, the engine management system was equipped with the designed control algorithm, which provides single-injection operation as well as coinciding the completion moment of fuel injection with the moment of inlet valve closure.
Carbon monoxide is considered as one of the pollutants of the internal combustion engine emissions due to incomplete combustion at high hydrocarbon concentrations. In addition, this gas is very dangerous because of its toxicity, and it is considered in all pollution tests. Therefore, carbon monoxide output from the exhaust was measured during the pollution cycle in all the tests, the changing trends of which are as shown in Figure 17.

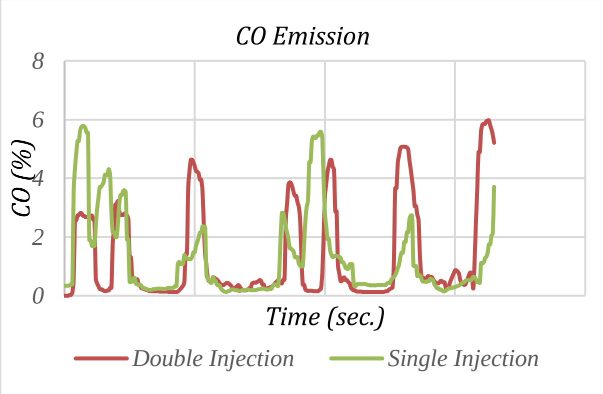

Figure 17: The mean carbon monoxide output measured during the emission cycle in percent

Not all hydrocarbons in the fuel can involve in the chemical reaction of combustion due to the lack of proper air-fuel mixture as well as inappropriate combustion. As a result, a part of the fuel is going out of the cylinder as raw and unburned, leading to the constitution of unburned hydrocarbons. Figure 18 shows the unburned hydrocarbons measured during the emission test cycle.

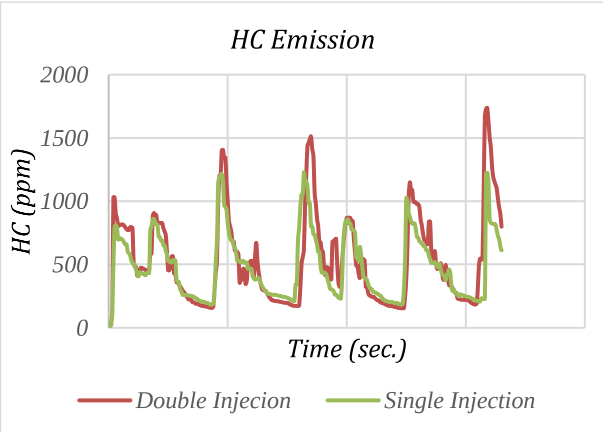

Figure 18: The amount of unburned hydrocarbons measured during the PPM pollutant cycle

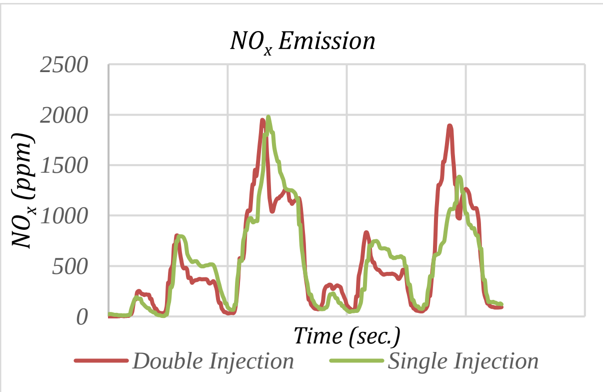

Figure 19: The measured nitrogen oxides output during the PPM pollution cycle

Similarly, Figure 19 displays the amount of produced nitrogen oxides during the pollutant cycle. Nitrogen oxide, which is formed inside the cylinder due to high pressure and temperature, is another pollutant in the exhaust of the combustion engine. Nitrogen and oxygen in the air react with each other and produce nitrogen oxide. Therefore, it is necessary to measure and control nitrogen oxides. Table 4 shows the average pollutants measured during the pollution cycle.

Table 4: The mean pollutants measured during the pollution cycle

	CO (%)	HC (ppm)	NO_x (ppm)
Double Injection	1.4	535.6	528.7
Single Injection	1.3	485.4	515.1

4) Discussion

Based on the performance structure of internal combustion engines, the performance of these engines is highly dependent on the fuel-air mixture. Making minor changes in the ratio of the air-fuel mixture so that the lambda can be equal to 0.98 results in the maximum output torque. However, the minimum emissions of pollutants such as carbon monoxide and unburned hydrocarbons are achieved through a leaner mixture which makes lambda equal to 1.03. A more accurate study indicates that if lambda equals 1, in addition to having the desired output power and torque, the output pollutants will be at a more desirable level [17]. Therefore, other different strategies can be used to decrease emission pollutants or increase engine power and torque through fixing the ratio of fuel and air in the stoichiometric range. Therefore, the way to prepare fuel-air mixing operations is considered as one of the issues which can be done more precisely to reduce emissions. In this regard, it is useful to perform a single-fuel injection operation and control its moment of starting or finishing based on the crankshaft angle in different conditions.

Using the valve position sensor is considered as one of the most common and reliable methods used in 4-cylinder internal combustion engines, however, it is not economical to be used in single-cylinder engines due to the increased production costs. Further, using this method can cause repairing complexities in the after-sales service sector. Regarding this, a new method should be implemented for detecting the

injection phase and changing the fuel injection operation from double-injection to single-injection operation. Therefore, this important problem can be solved through a suggested method, without using the valve position sensor. The results of simulation and experimental tests indicated that the capability of converting the fuel injection operation from double-injection operation to single-injection mode is available according to the information received from the manifold pressure sensor and the engine speed.
Furthermore, the process of reducing the emission pollutants at each stage can be observed based on the pollutant tests. Therefore, the emissions pollutants were significantly reduced in the first step by changing the fuel injection system from carburetor to the electric fuel injection. The process of these changes is that the mean carbon monoxide decreased by 45.7% during the cycle, the mean unburned hydrocarbons decreased by 21.3%, and the mean nitrogen oxides decreased by 2.3%.
The studies related to the change in the fuel control system of motorcycles with engine volume less than 150cc indicate that the process of reducing each pollutant is perfectly reasonable [18, 19, 20]. However, based on the experiment tests, it is found that the mean carbon monoxide output decreased by 5.9%, the mean unburned hydrocarbons as 9.4%, and the nitrogen oxides as 2.6%, respectively, after implementing the designed algorithm and the single-fuel injection operation, compared to when the fuel injection operations were performed at each crankshaft revolution.
Based on the studies on the process of fuel-air mixture preparation and fuel injection during the intake stroke due to the crankshaft angle in the internal combustion engines whose fuel is injected into the inlet manifold, the results of the pollutant test can be verified [2, 5, 6].

5) Conclusions

Based on the results, the following conclusions were drawn:

- Single-fueling operations through manifold pressure sensor information on single-cylinder engines are well possible at idle speeds.
- Single-fuel injection operation can be conducted in all conditions including part load and full load through synchronizing fuel injection phase detected by pressure sensor information in idle condition with the signal received from the engine speed sensor
- The moment of initiating the fuel injection can be conducted at various angles of the crankshaft so that the fuel injection operation is completed before the inlet valve closure due to the identification of the moment of closing the inlet valve based on the pressure sensor information, engine speed, as well as valve timing
- Applying this method without increasing production costs improves the performance of the engine management system
- Performing single-fuel injection operations reduces the exhaust emissions such as carbon monoxide, unburned hydrocarbons, and nitrogen oxides.

Further, it is found that using strategies such as phase control is not only useful but also essential by examining the trends of changes in the amount of permissible emitted pollutants in Euro 4 and Euro 5 emission standards.

Acknowledgments

Conducting research related to controlling the environmental pollutants results from the operation of internal combustion engines requires genuine scientific, material, and spiritual support. Therefore, the authors of this article consider it necessary to express their gratitude for the unsparing support of the distinguished chair and staff of the Management and Engineering Unit of Negarin Sanat Asia Co. and the management and staff of the Danesh Tajhiz Farzaneh Company.

List of Symbols

C_d	Discharge Coefficient
v	Flow velocity
k	Specific heat ratio
P	Static pressure
r	Density
S_1	Cross-sectional of the upstream area
S_2	Throttle opening area
n	Polytropic index
V_3	The volume of stagnation region
W	Work of the piston
x	Piston Position
θ	Crank angle

l_c	Length of connecting rod
l_s	Length of stroke
V_{TDC}	Combustion chamber volume
S_4	Piston cross-section area
t_{IVC}	Inlet valve closure time
A_p	Initial amplitude
τ_p	Damping constant time
ω_p	Angular velocity
θ_p	Initial phase angle
$X(f)$	Spectrum values
$X(t)$	Signal in time domain
f	Frequency
f_s	Data Frequency
f_c	The maximum frequency available in the signal
$x[\,]$	Input signal
$y[\,]$	Output signal
β	Intake stroke (rad)
N	Engine Speed
IT	Fuel injection time
A_p	Initial amplitude
τ_p	Damping constant time
ω_p	Angular velocity
θ_p	Initial phase angle
α	The moment of opening of the inlet valve after receiving the crankshaft position signal
IST	The interval between the moment of receiving crankshaft position signal and the moment of fueling operation

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تارنمای فصلنامه: www.engineresearch.ir

DOI:10.22034/ER.2022.697903

تأثیر زمان‌بندی و فازبندی تزریق سوخت بر آلایندگی موتور تک‌استوانۀ بنزینی

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اطلاعات مقاله

تاریخچۀ مقاله:

دریافت: ۱۰ مرداد ۱۴۰۰

پذیرش: ۲۸ اسفند ۱۴۰۰

کلیدواژه‌ها:

موتور تک استوانه

تشخیص فاز سوخت

زمان‌بندی تزریق

موتور چهارزمانه

مهار آلایندگی موتور

چکیده

ارزیابی عملکرد موتورهای احتراق داخلی و تعیین استانداردهای مختلف آلایندگی، اهمیت کاهش آلایندگی و همچنین مصرف بهینۀ سوخت در این موتورها را آشکار کرده است. بر همین اساس، سامانه‌های مدیریت موتور مورد استفاده قرار می‌گیرند که از طریق تهیه مخلوط هوا و سوخت مناسب، منجر به بهینه‌سازی توان و کاهش انتشار آلاینده‌های خروجی می‌شوند. سامانه‌های مدیریت موتور امروزه قادر به تعیین و تأمین دقیق مخلوط هوا و سوخت هستند. با این‌حال، عملکرد موتورهای احتراق داخلی که سوخت آن‌ها در داخل چندراهۀ ورودی پاشش می‌شود، بسیار وابسته به زمان عملیات سوخت‌رسانی است که فاز تزریق سوخت نامیده می‌شود. روش‌های مختلفی جهت تشخیص فاز تزریق سوخت وجود دارد که متداول‌ترین آن‌ها استفاده از حسگر موقعیت میل بادامک است. بااین‌وجود، این موضوع همچنان به‌عنوان یکی از چالش‌هایی که بیشتر کار محققان را به خود اختصاص داده است، در نظر گرفته می‌شود. چراکه استفاده از حسگرهای موقعیت میل بادامک و موارد مشابه منجر به افزایش هزینه‌های تولید و همچنین برخی پیچیدگی‌ها در خدمات پس از فروش می‌شود. بنابراین، این تحقیق با هدف طراحی یک الگوی مدیریتی برای تعیین فاز تزریق سوخت و همچنین شناسایی لحظه بسته شدن دریچۀ ورودی با ارزیابی دادۀ حسگر فشار چندراهۀ ورودی موتور تک استوانه انجام شده است. در مرحله بعد این قابلیت به سامانۀ مدیریت موتور اضافه و عملکرد آن ارزیابی شد. نتایج به‌دست‌آمده نشان داد که تعیین فاز تزریق از طریق این روش به‌خوبی امکان‌پذیر است. علاوه بر این، به‌منظور شناسایی تأثیر این الگو بر کاهش آلاینده‌های خروجی، آزمون آلایندگی ECE-R40 انجام و نتایج آن با سطح آلاینده‌های خروجی در زمانی که سامانۀ مدیریت موتور مجهز به این الگو نبود، مقایسه شد. این مقایسه نشان می‌دهد که با استفاده از الگوریتم تشخیص فاز، میانگین مونوکسید کربن، هیدروکربن‌های نسوخته و اکسیدهای ازت هر کدام به ترتیب ۵,۹، ۹,۴ و ۲,۶ درصد کاهش می‌یابد.