Journal of Solid and Fluid Mechanics (JSFM), 14(6): 1-4, 2025

Shahrood University of Technology

Journal of Solid and Fluid Mechanics (JSFM)

DOI: 10.22044/jsfm.2025.15181.3901

Manufacturing Engineering of Iran

Numerical investigation of combustion and intake valve timing on the performance of TU5 spark ignition engine

Javad Azarkhazin[1], Karim Aliakbari[2,*], Mohammad Sheykhi[3], Seyyed Mohammad Mahdi Delavari[4]

[1] MSc. Student, Mech. Eng., Technical and Engineering Faculty, Eqbal Lahoori Institute of Higher Education, Mashhad, Iran
[2] Assoc. Prof., Mech. Eng., Department of Mechanical Engineering, National University of Skills (NUS), Tehran, Iran
[3] Ph.D., Mech. Eng., Department of Mechanical Engineering, National University of Skills (NUS), Tehran, Iran
[4] BSc., Automot. Eng., Department of Mechanical Engineering, National University of Skills (NUS), Tehran, Iran
*Corresponding author: karim-aliakbari@nus.ac.ir; karim.aliakbari@gmail.com

Received: 10/07/2024 Revised: 01/02/2025 Accepted: 01/22/2025

Abstract

Spark and intake valve timings are key operating parameters of spark ignition engines that determine the initial combustion process and the intake air amount during engine operation. Therefore, determining the appropriate timing for spark initiation and breathing are important factors for improving engine performance and complete combustion. The present work aims to evaluate the effects of spark and intake valve timings and the appropriate selection of compression ratio at different speeds on the TU5 engine performance using a numerical method. To achieve this goal, first, numerical simulation results are compared with experimental results and validated, then the effects of engine technical parameters, including compression ratio, combustion and intake valve timings at different speeds on characteristics of power, torque, mean effective pressure, volumetric efficiency, thermal efficiency, and specific fuel consumption are investigated. The results showed that engine output characteristics at 4000 rpm have the best performance. Also, the optimal advance for maximizing power and torque and the lowest specific fuel consumption is 5 and 10 degrees before the top dead center (TDC) at 2000 and 4000 rpm, respectively. In addition, by selecting the intake valve advance angle at about 30 degrees before the intake process, volumetric efficiency will reach about 97 percent.

Keywords: TU5 engine; Spark timing; Intake valve timing; Special fuel consumption; Optimal advance.

1. Introduction

Considering some important issues such as regulations to reduce air pollutant emissions and lower fuel consumption of vehicles, optimizing fuel consumption in internal combustion engines will interest all major engine manufacturers worldwide. For this purpose, several technologies have been considered and some of them are currently widely used as commercial technologies in new vehicles [1]. Optimizing the spark timing, increasing volumetric efficiency, and increasing the fuel injection pressure of the engine are among the methods that improve fuel efficiency and engine performance. Increasing the amount of air entering the cylinder and optimizing the spark timing in a conventional engine, reduces fuel consumption and increases engine power [2]. Spark timing is very important in achieving maximum engine pressure and fuel consumption. When the spark occurs earlier, the maximum cylinder pressure is higher and occurs earlier.

In this study, with the help of commercial software called AVL BOOST, a numerical simulation of the TU5 combustion engine was performed with appropriate accuracy. Then, for the first time, the effects of important engine parameters, including the ignition start angle, combustion duration, compression ratio, and intake valve opening time at different speeds were investigated on the engine performance characteristics, including power, torque, and specific fuel consumption. The optimal ranges of the operating conditions of this engine were reported. In previous studies, the effects of the mentioned parameters on the performance of the TU5 engine were not discussed simultaneously using numerical simulation.

2. Numerical Simulation Procedure

2.1. Numerical Model Design

In this work, AVL BOOST commercial software has been used to model the TU5 gasoline spark ignition engine. The TU5 engine is a four-cylinder in-line engine designed and manufactured by Iran Khodro Company. This engine is designed from the ground up to run on natural gas fuel and is also capable of running on gasoline.

2.2. Governing Equations

In this study, combustion is performed in two zones.

Thus, the cylinder contents are divided into two parts at the beginning of combustion: burnt and unburned (Figure 1). Therefore, the energy equation for each time step for the unburned and burnt zones is rewritten according to equations (1) and (2), respectively.

$$\frac{d(m_u e_u)}{dt} = -p\frac{dV_u}{dt} - Q_u + \left(\frac{dm_f}{dt}H_f + \frac{dm_a}{dt}H_a\right) + \frac{dm_{f,i}}{dt}h_{f,i} \quad (1)$$

$$\frac{d(m_b e_b)}{dt} = -p\frac{dV_b}{dt} - Q_b + \left(\frac{dm_f}{dt}H_f + \frac{dm_a}{dt}H_a\right) \quad (2)$$

Here, the subscripts u and b denote the unburned and burned zones, respectively, and the subscripts i and f denote the sprayed fuel. Note that here Q is the heat transfer rate and the burning rate is given by $\frac{dm_f}{dt}$.

The Wiebe function is used to model the combustion. The amount of the burned composition at each set time is obtained from the Wiebe function. For all other terms, such as wall heat losses, etc., the same models as the single-zone models are applied with appropriate distribution in the two zones [3].

$$x = 1 - exp\left[-a\left(\frac{\alpha - SOC}{BDUR}\right)^{m+1}\right] \quad (3)$$

where SOC, $BDUR$, α, m, and a are the ignition start, burning time, crank angle, Wiebe shape, and Wiebe parameter, respectively. In addition, the heat transfer model of [4] has been used to model the heat transfer between the gas and the cylinder wall.

The effect of changes in the flow characteristics of the engine can be investigated by defining three important criteria: effective torque (T_{eff}) in Nm, effective power (P_{eff}) in kW, and effective thermal efficiency (η_{theff}) in percent, which are defined as equations (4)-(6) respectively [5,6].

$$T_{\text{eff}} = \frac{P_{\text{eff}}}{n_m}\left(\frac{6000}{2\pi}\right) \quad (4)$$

$$P_{\text{eff}} = \frac{\oint T(t) n_m dt}{\oint dt}\left(\frac{2\pi}{6000}\right) \quad (5)$$

$$\eta_{theff} = \frac{P_{\text{eff}}}{CV\dot{m}_f} \quad (6)$$

Where n_m, CV, and $\dot{m}_f$ are the engine speed (rpm), the lower calorific value of the fuel (kJ/kg), and the fuel consumption (kg/s), respectively.

2.3. Solution Method

The method of solving the equations is the initial value numerical method and the following assumptions are taken into account for the solution:

1. The numerical solution method of the engine differential equations is the Runge-Kutta method.
2. The angular step is considered to be one degree and the number of iterations is 50.
3. The convergence condition is based on pressure.
4. Simple two-zone models assume that the cylinder has a burning zone and an unburned zone at all times during the combustion process (Figure 1).

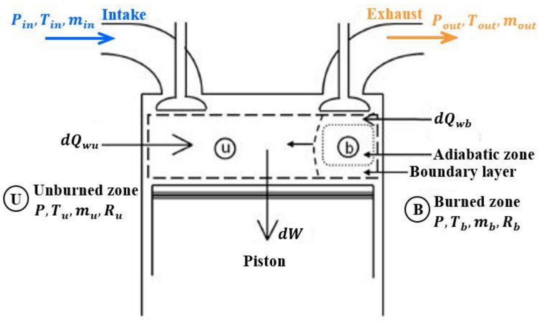

Figure 1. Schematic diagram of the thermodynamic system.

3. Result Analysis

In this section, the model used to analyze the performance of the combustion engine is first validated, and then the effect of various engine parameters on the performance of the system is examined.

3.1. Results Validation

Thus, to validate the model used to analyze the performance of the combustion engine, the characteristics of the TU5 gasoline engine were used (Table 1) and the model results were compared with the experimental results of this engine and other previous models. In Figure 2, the effective power of the TU5 engine for the present model and the experimental results [7] are compared at different speeds. The results of the present model in estimating the effective power indicate that it is valid and the accuracy of the present modeling is high compared to other proposed models.

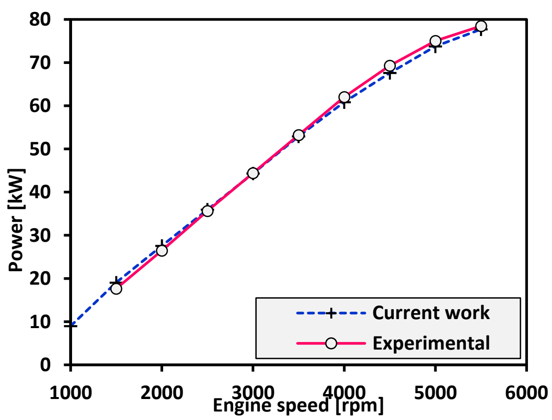

Figure 2. Validation of the present model power at different engine speeds.

Table 1. Validation of the present model with the experimental method [7] at 4000 rpm.

Parameter	Experimental	Current work
Power [kW]	62.02	60.85
Power error [%]	0	-1.89

3.2. Results Analysis

In Figure 3, the effect of compression ratio at different speeds on the performance of effective power from the TU5 engine is analyzed. As the engine compression ratio increases, engine pressure is imporved, causing an increase in power and torque, and as it is clear, with the increase in compression ratio at high speeds, the rate of increase in power and torque is greater, or in other words, at high speeds, the rate of increase in power and torque with increasing compression ratio (engine pressure) is greater than the rate of decrease in power and torque with increasing friction and losses, and power and torque increase noticeably in these conditions.

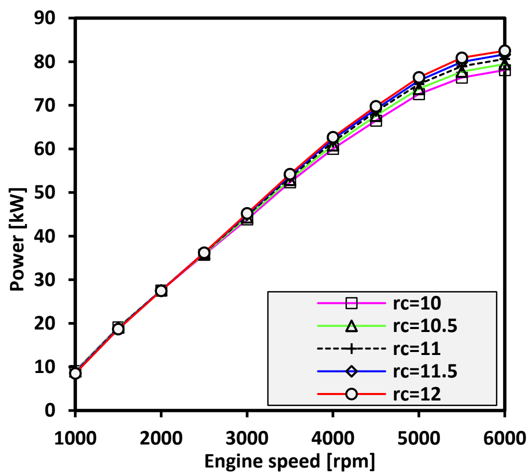

Figure 3. The effect of compression ratio on system effective power at different engine speeds.

In Figure 4, the effect of ignition start angle and combustion duration on the power of the TU5 engine at 4000 rpm has been analyzed. The results of numerical modeling show that at high rpm, in order to achieve more complete and powerful combustion, the ignition start time should be advanced. Therefore, it is better to advance the spark start time at 4000 rpm compared to 2000 rpm. Thus, the optimal advance for maximizing power at speeds of 2000 and 4000 rpm is -5 and -10 degrees before TDC, respectively.

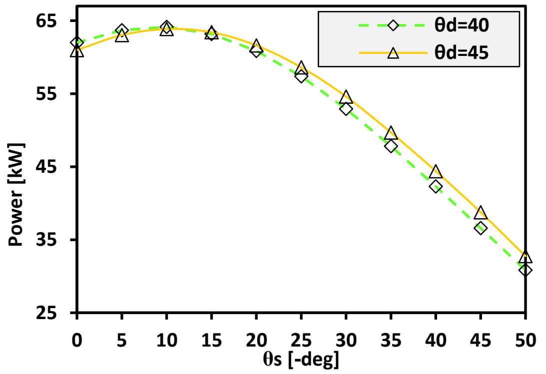

Figure 4. Effect of ignition start time and combustion duration on effective power at 4000 rpm.

Figure 5 shows the effect of ignition start angle and combustion duration on the specific fuel consumption of the TU5 engine at 4000 rpm. Similarly, it is clear that at higher rpm, to achieve the lowest specific fuel consumption, the spark start angle should be advanced and the combustion duration does not change much on the specific fuel consumption efficiency, especially at advance angles less than -20 degrees from TDC.

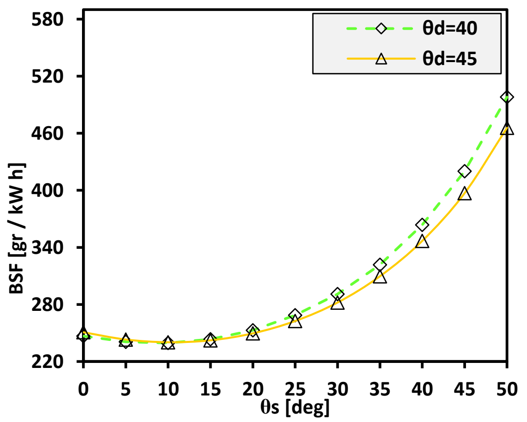

Figure 5. Effect of ignition start time and combustion duration on specific fuel consumption at 4000 rpm.

Another parameter that is important in the performance of the combustion engine is the time of opening and closing of the intake valve at different speeds. If this parameter is adjusted correctly, internal combustion engines have better breathing and the highest amount of power and efficiency is achieved. Figure 6 models the effect of the intake valve advance angle at 5000 rpm on the volumetric efficiency and mean effective pressure of the engine. As mentioned, at higher speeds, it is better to reduce the intake valve advance angle so that the time of closing the intake valve is delayed so that the engine has better breathing. Thus, at 5000 rpm, the optimal advance angle is about -10 degrees relative to the start of the intake process, and in these conditions, the volumetric efficiency and mean effective pressure reach about 0.90 and 9.33 bar, respectively.

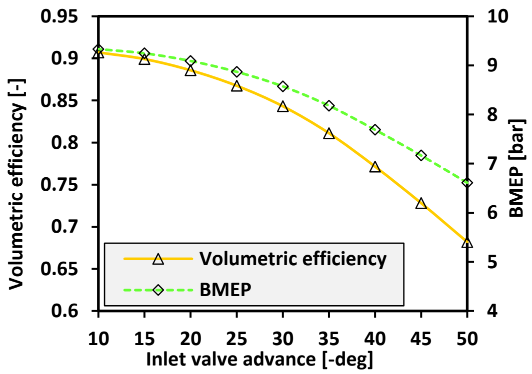

Figure 6. Effect of intake valve advance angle on volumetric efficiency and mean effective pressure at 5000 rpm.

4. Conclusions

In this paper, the effects of the performance characteristics of the TU5 combustion engine, including the ignition start time, combustion duration, compression ratio, and engine speed, on performance were investigated using numerical simulation, and the following results were obtained:

1. The numerical model, in addition to having appropriate accuracy, is capable of determining the optimal speed range within the 4000-rpm limit to achieve the highest torque.
2. The results showed that the engine characteristics of torque, specific fuel consumption, power, and efficiency have the best performance at 4000 rpm.
3. Advancing the combustion time at different speeds can have positive and negative effects on engine performance. Thus, the optimal advance for maximizing power and torque and achieving the lowest specific fuel consumption at 4000 rpm is 5 and 10 degrees before TDC, respectively.
4. Given that as the compression ratio increases, a greater percentage of the energy input to the engine is converted into effective power, increasing the compression ratio always reduces specific fuel consumption.
5. At high rpm, in order to achieve the lowest specific fuel consumption, the ignition start angle should be advanced, and the combustion duration does not change much on the specific fuel consumption performance, especially at advance angles less than 20 degrees from TDC.
6. At low speeds (around 2000 rpm) the intake valve advance angle should be increased and its optimum range for achieving the highest volumetric efficiency is around 30 degrees before the start of the intake process. In this condition, the engine breathes better and the volumetric efficiency reaches 0.97.
7. At 5000 rpm the optimum advance angle will decrease and its value is around -10 degrees compared to the start of the intake process and in this condition the volumetric efficiency and the mean effective pressure reach around 0.90 and 9.33 bar respectively.

5. Reference

[1] Kakee A-H, Sharifipour S, Mashadi B, Keshavarz M, Paykani A. (2015) Optimization of spark timing and air-fuel ratio of an SI engine with variable valve timing using genetic algorithm and steepest descend method. *UPB Sci Bull Ser D Mech Eng.* 77: 61–76.
[2] Talati H, Aliakbari K, Ebrahimi-Moghadam A, Farokhad HK, Nasrabad AE. (2022) Optimal design and analysis of a novel variable-length intake manifold on a four-cylinder gasoline engine. *Appl Therm Eng*. 200: 117631.
[3] AVL List Gmbh, (2013) *AVL Boost – Theory*.
[4] Iliev SP. (2015) Developing of a 1-D Combustion model and study of engine performance and exhaust emission using ethanol-gasoline blends. *Trans. Eng. Technol. World Congr. Eng. Springer*. p. 85–98.
[5] Silva EAA, Ochoa AA V, Henríquez JR. (2019) Analysis and runners length optimization of the intake manifold of a 4-cylinder spark ignition engine. *Energy Convers Manag.* 188: 310–20.
[6] Ceviz MA, Akın M. (2010) Design of a new SI engine intake manifold with variable length plenum. *Energy Convers Manag*. 51: 2239–44.
[7] Kashi SS, Qasemian A. (2022) Utilization of Stirling engine to improve the performance and fuel consumption of an internal combustion engine by exhaust gas heat recovery. *J Engine Res*. 66: 68–84