academicJournals

Vol. 8(19), pp. 934-945, 23 May, 2013
DOI: 10.5897/IJPS10.445
ISSN 1992 - 1950 © 2013 Academic Journals
http://www.academicjournals.org/IJPS

International Journal of Physical Sciences

Review

Numerical investigation on the effect of different parameters on the performance and the emission of a spark ignition (SI) engine

H. Mirgolbabaei[1]*, M. Bozorgi[2] and M. M. Etghani[2]

[1]Young Researchers Club, Islamic Azad University, Jouybar Branch, Jouybar, Iran.
[2]Automotive Engineering Department, Iran University of Science and Technology, Tehran, Iran.
[3]Department of mechanical engineering, Babol Noshirvani University of Technology, Babol, Iran.

Accepted 21 October, 2010

In this work, NISSAN Z24 engine was simulated numerically and valves and ignition timings were modified in order to improve the engine performance and emissions. The engine was simulated using a version of the Los Alamos code KIVA-3V2 which is a computer program for the numerical calculation of transient, two and three dimensional chemically reactive flows with sprays. The computational grid was generated by the commercial software, ANSYS ICEM CFD. To validate the code, a comparison between experimental and theoretical results has been made, which confirm good qualitative agreement between these results. A series of parametric studied is performed to gain a better understanding of the effects of valves and ignition timings on the engine performance and emission. The results show that the engine volumetric efficiency, output power, emissions and performance are well improved by applying the optimal values.

Key words: Spark ignition (SI) engine, valves and ignition timings, engine performance and emissions.

INTRODUCTION

Nowadays, due to government server rules on environmental standards and fuel consumption, car manufacturers are under pressure to reduce regulated emissions and fuel consumption. Valves and ignition timings are known as a very effective process on output power, emissions and engine performance. The improvements can be achieved with the lowest change in the engine and hence less cost. Shayler (2007) investigated the effect of valve timing on the amount of burned gas that remains from pervious cycle in the combustion chamber. He concluded that valve timing has a noticeable effect on the entrance of a fresh mixture. This effect is because of valves overlap. At this moment, some burned gas that remains from pervious cycle enters into the intake manifold, pushes back the fresh mixture and reduces the volumetric efficiency. This event is more important in low speed of the engine, since at engine low speed, the engine has a longer overlap. Siewert (1971) studied the effect of valve timing on the emissions. He found that these effects are more noticeable in NOx and HC emission. Also he found that by controlling the temperature of the combustion chamber according to the amount of burned gas that remains from pervious cycle, the amount of NOx can be reduced. This event can take place by adjustment of valve timing and valve overlap. Furthermore, the amount of vapor of gasoline that leaves

*Corresponding author. E-mail: hesam_peeter@yahoo.com.

the combustion chamber through the exhaust valve at valve overlap can be reduced by exact adjustment of valve timing. Tuttle (1980, 1982) considered the effect of early or late intake valve opening on the output power of the engine. Smith et al. (1984) performed some experimental research about knock and the factors affect on it. They found that compression ratio and ignition timing are tow the most important factors that have a great effect on knock. Zhu et al. (2004) investigated the ignition timing and some limitation for choosing the ignition timing. They concluded that if we advance the ignition timing more than a suitable point it leads to knock and if we retard the ignition timing it may lead to misfiring. Boyce et al. (1999) did some research in the effect of an ignition timing and air/fuel ratio on the release of energy in combustion chamber and temperature of a combustion chamber. They found advancing the ignition timing increase the rate of energy release and temperature of the combustion chamber. Duclos et al. (1996) simulated combustion and emissions in an SI engine using KIVA and found the effect of a residual gas and spark plug situation on the engine performance. Eckert et al. (2003) simulated knock by KIVA-3V. They validated their results with an experimental test. In the present study, the improvement of the engine volumetric efficiency is performed numerically, using the method “Improving” considering the valve timing of the engine.

VOLUMETRIC EFFICIENCY

The intake system (the air filter, throttle plate, intake manifold, intake port, intake valve) restricts the amount of air which an engine of given displacement can induct. The parameter used to measure the effectiveness of an engine’s induction process is the volumetric efficiency. It is defined as the volume flow rate of air into the intake system divided by the rate at which volume is displaced by piston:

$$\eta_v = \frac{2\dot{m}_a}{\rho_{a,i} V_d N} \tag{1}$$

Volumetric efficiency is mainly affected by the fuel, engine design and engine operating variables in terms of Heywood (1988): Fuel type, fuel/air ratio, fraction of fuel vaporization in the intake system and fuel heat of vaporization, mixture temperature as influenced by heat transfer, ratio of exhaust and intake manifold pressure, compression ratio, engine speed, intake and exhaust manifold and port design, intake and exhaust valve geometry, size, lift and timing. There are lots of methods can be used for the better operating condition of engine (more output power and less emission). For example we can consider these methods (Pulkrabeck, 2003): Increasing the intake and exhaust valves diameter, increasing the number of intake valve, using of some new methods like Gasoline Direct Injection (GDI), variable valve timing (VVT), improving the valve timing of the engine. In this paper, the last method (improving the valve timing of the engine) is used for improving the engine volumetric efficiency. Intake and exhaust valve timing has great effect on volumetric efficiency. Reverse flow into the intake manifold (it takes places at the valve overlapping) and the temperature of fresh air and fuel mixture when the intake valve opens are two important items depending on valve timing and have great effect on volumetric efficiency (Siewert, 1971). Furthermore, valve timing has a great effect on HC and NOx. We can reduce the amount of HC by adjusting the valve overlap. Also we can reduce the amount of NOx by adjusting the amount of burned gas that remains from pervious cycle in a combustion chamber. Since this burned gas causes the leaner mixture in the combustion chamber, it leads to decrease in the maximum temperature of a combustion chamber. NOx has a direct relationship with the maximum temperature of a combustion chamber and it can be adjusted by exact adjusting the valve timing (Shayler, 2007).

Combustion in a spark ignition (SI) engine and the factors which control it

In a conventional spark ignition engine, the fuel and air are mixed together in the intake system, inducted through the intake valve into the cylinder, where mixing with residual gas takes place and then compressed. Under normal operating conditions, combustion is initiated towards the end of the compression stroke at the spark plug by an electric discharge. Following inflammation, a turbulent flame develops, propagates through this essentially premixed fuel, air, burned gas mixture until it reaches the combustion chamber walls, and then extinguishes. According to our knowledge about a SI engine’s combustion progress (ignition and development of flame, propagation and quenching), we can find the relation between physical and chemical factors which control the combustion and the design of engine. Numbers of factors affecting combustion and propagation of the flame are (Ferguson and Kirkpatrick, 2001): Geometry of combustion chamber and situation of spark plug in the cylinder head; fluid flow’s characteristic which include velocity of the fluid; turbulence intensity and unburned gas turbulence characteristic, and unburned mixture state and combination like fuel equivalence ratio, pressure and temperature of mixture and ignition timing. In this paper, improving the ignition timing is used for improving the combustion characteristics. Ignition timing in SI engine has a great effect on air and fuel mixture combustion quality, since by exact adjustment of ignition timing we can adjust the maximum pressure angle of the combustion chamber (around 10 to 15° ATDC) in the best situation. Therefore, the output power of the engine

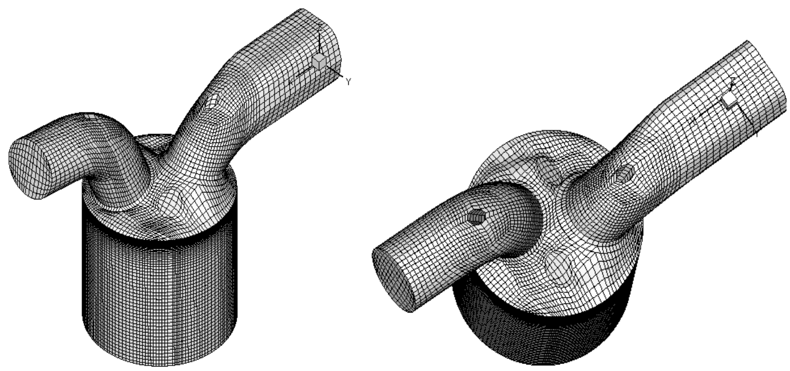

Figure 1. Computational grid generated in ICEM CFD.

Table 1. Specification of NISSAN Z24.

Bore × stroke (mm)	89 × 96
Compression ratio	8.4
Power (kW/cyl)	137
Air/fuel ratio	14
Number of holes/hole diameter (mm)	8/0.4
Fuel amount (g/cycle)	0.0453
Rpm	2800
Cylinder pressure at IVC (bar)	3.6
Air temperature at IVC (K)	400
Wall temperature (K)	Wall: 45 Head: 500 Piston: 550
Valve timing	IVO: 9 BTDC IVC: 37 ABDC EVO: 41 BBDC EVC: 5 ATDC
Type	4 cylinder,4 cycle
Max. motoring / firing pressure at full load and 2800 rpm (bar)	14.5/52

increases and the HC and CO emission decreases (Heywood, 1988). Of course, it should be noticed that a little change in ignition timing can lead to misfire or knock (Ferguson and Kirkpatrick, 2001).

Abnormal combustion reveals itself in many ways. One of the most important abnormal combustion processes important in practice is knock. Knock originates in the extremely rapid release of much of the energy contained in the end-gas ahead of the propagation turbulent flame, resulting in high local pressures. The non uniform nature of this pressure distribution causes pressure waves or shock waves to propagate across the chamber, which may cause the chamber to resonate at its natural frequency (Heywood, 1988). The two important factors, which affect knock are air/fuel ratio and ignition timing. We can prevent it by exact adjustment of these two factors (Pulkrabeck, 2003).

Numerical simulation

Figure 1 shows the computational mesh of the engine combustion chamber and ports, which is created in ICEM-CFD. There are about 67000 cells in the entire computational domain. The reference point of z = 0 cm is defined as the lowest axial point of the piston bowl at BDC. The engine is the NISSAN Z24 engine. The specifications of the engine and calculating conditions are given in Table 1. The calculation starts 251 crank angles before IVO and continues 720 crank angles for example, a full cycle calculation including intake and exhaust processes. For initial conditions, the gas temperature,

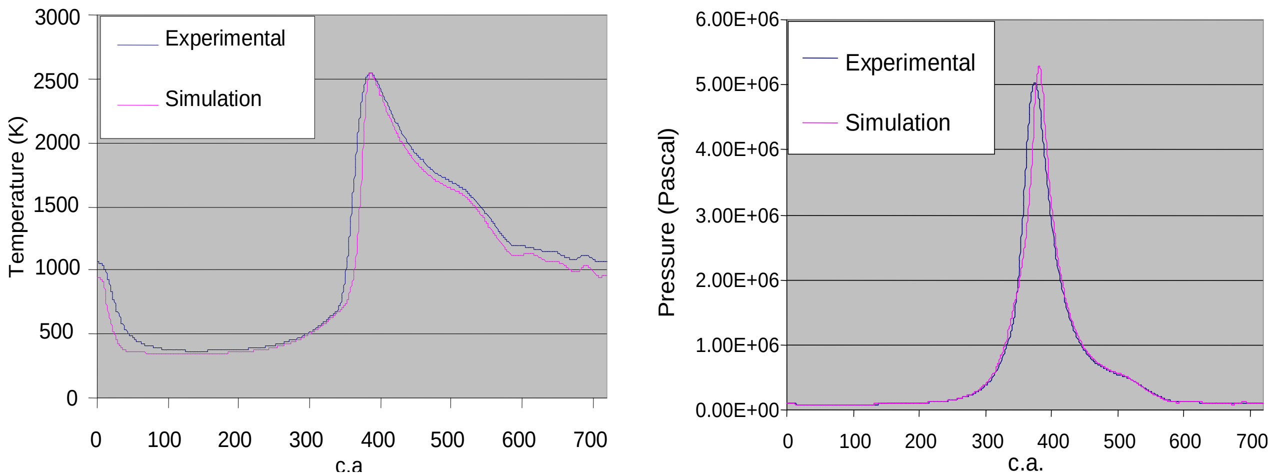

Figure 2. Validation of numerical results against measured data.

Table 2. NISSAN Z24 engine valve timing.

IVO	9 c.a BTDC
IVC	37 c.a ABDC
EVO	41 c.a BBDC
EVC	5 c.a ATDC

Table 3. Different valve timing.

State	IVO at 5 c.a BTDC	IVO at 12 c.a BTDC
IVO	5 c.a BTDC	12 c.a BTDC
IVC	43 c.a ABDC	35 c.a ABDC
EVO	36 c.a BBDC	43 c.a BBDC
EVC	10 c.a ATDC	3 c.a ATDC

pressure and species densities were assumed to be uniform in the entire combustion chamber.

Validation

For validation, the result that is driven from KIVA 3 V, the experimental data like the pressure and the temperature of the cylinder is used as shown in Figure 2. The curves in intake, compression and expansion phases are close together but there is around 5% difference between the experimental and simulation curves in ignition phase. There is an important reason for this difference; the fuel that we use in the experimental test is not standard. Consequently, the factors of chemical reaction rate of KIVA 3 V are calibrated for this case by exact adjustment. It should be noticed that all the calculations are performed in this situation. The engine speed is 2800 rpm and Ø=1, since the engine maximum torque happens in these situations.

Improving the volumetric efficiency of the engine by changing the valve timing

The NISSAN Z24 engine valve timing is mentioned in Table 2. The volumetric efficiency of NISSAN Z24 is 87% and the amount of volumetric efficiency that is calculated with KIVA 3 V is 92%. This difference is because of ignoring the ram effect in the intake system. To improve the volumetric efficiency of the engine by changing the valve timing, without changing the cam profile, we can only replace the cam angle according to its last position and the TDC position. Therefore, we considered the various situations of this concept. Table 3 presents these various situations. Figure 3 shows the effect of these changing on cylinder pressure. As shown in Figure 3, the IVO at 12 C.A BTDC is the best because between all situations; the maximum cylinder pressure and consequently, the maximum output power of the engine are obtained. Table 4 presents the exact changing amount; also Figure 4 shows the difference of cylinder pressure between Z24 and improved Z24. As shown in Table 4, the volumetric efficiency of improved Z24 is 94%, which has 2% improvement in comparison with Z24; also the engine power increased almost 1%. On the other hand, as shown in Table 5, the efficiency of exhaust process is calculated and it shows the new valve timing has the better efficiency of exhaust process almost 0.1%.

Improving the ignition timing

Ignition timing was optimized in order to increase the engine power and decrease the emission. There are some limitations in changing the ignition timing. For

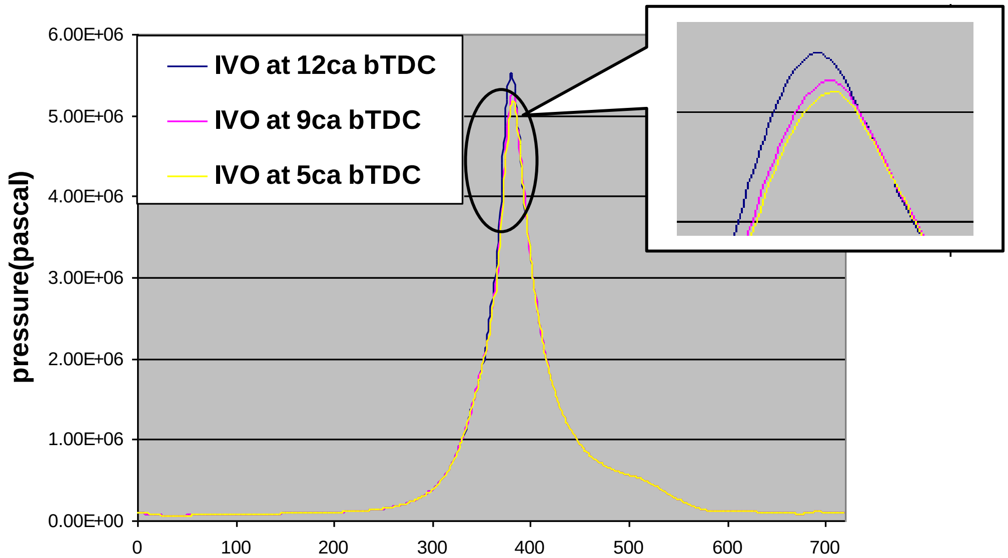

Figure 3. Combustion chamber pressure in 3 different valve timing.

Table 4. Exact changing amount of Z24 in new situation.

Parameter	Unit	Z24	Improved Z24
Mass of mixture	g	0.62313	0.64762
Mass of fuel	g	0.0453	0.0453
Displacement volume	cm^3	600	600
Air temperature before entrance of cylinder	K	332	325
Air density in air temperature before entrance of cylinder	g/cm^3	0.00106	0.001079
Volumetric efficiency	%	0.92	0.94

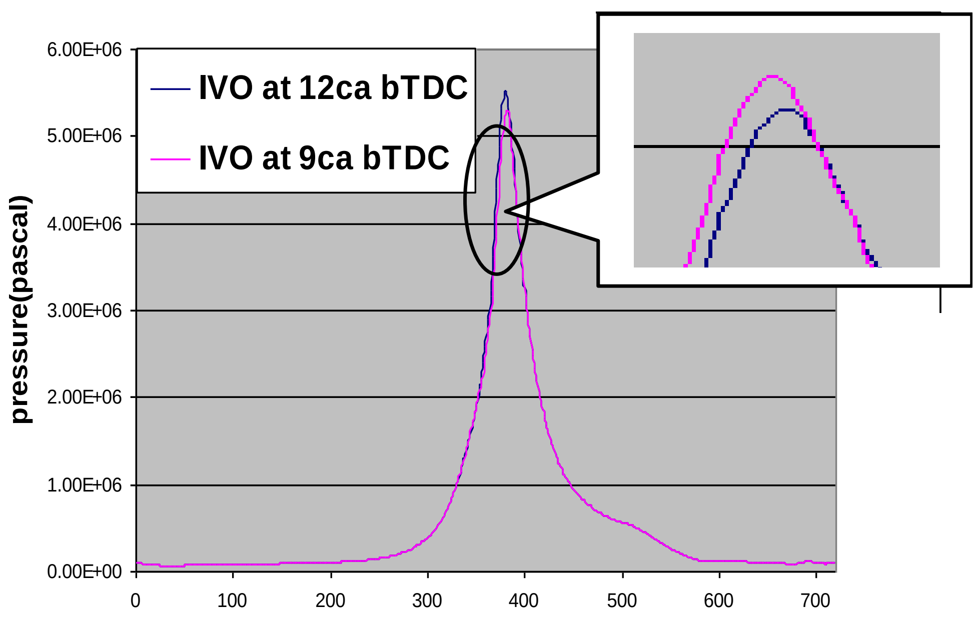

Figure 4. Combustion chamber pressure in Z24 and improved Z24.

Table 5. The efficiency of exhaust process.

State	Unit	IVO at 9 c.a BTDC	IVO at 12c.a BTDC (improved η_v)
Mass of mixture	g	0.62312	0.64762
Mass of burned gas remained in combustion chamber from pervious cycle at IVO	g	0.0247	0.02066
Efficiency of exhaust process	%	96.04	96.16
3 c.a ATDC	EVC		

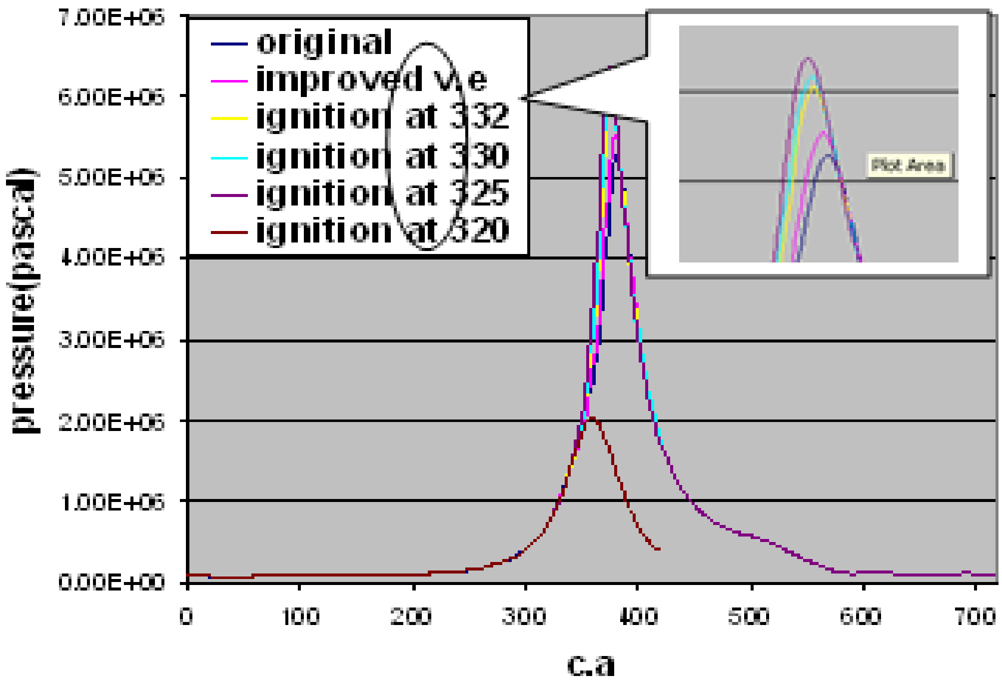

Figure 5. Pressure of combustion chamber in different ignition timing.

example, if we want to retard the ignition timing, although it leads to decrease in the NOx emission and prevention of knock, it may leads to increase in the HC emission. And advancing the ignition timing leads to knock, increasing the NOx emission and decreasing the engine power, so we should choose the best ignition timing that leads to the more power and less emission. Furthermore, in advancing the ignition timing, we have to consider the endurance of the cylinder head against the cylinder pressure. Another important item that we must notice to it is the probability of knock formation. Furthermore, after each change, we have to check it. The ignition timing of Z24 engine in 2800 rpm is 23° BTDC. So if we assume TDC at intake process, as our basis, the time of ignition is 336°. To reach the best ignition timing, we did simulation in some different ignition timing. Simulation was done in 332, 330, 325 and 320°. Outputs of these calculations are shown in Figure 5. You can see the cylinder pressure of these states in this figure. Also the amount of NOx, HC, CO and CO_2 in these states is shown in Figures 7 to 10. It should be noticed that all the calculations in this part were done on the base of new valve timing that was done in the perviously.

As shown in Figure 5, advancing the ignition timing 35° is the best because the maximum output power is released. If we increase the advancing angle of the ignition, it leads to decreasing the output power and finally misfiring. We can confirm this claim with ignition timing at 320° as shown in Figure 5. So we choose the ignition timing at 325° and for stabilizing this angle, we should check these points:

1. Calculation of the output power in this case and compare it with original engine.

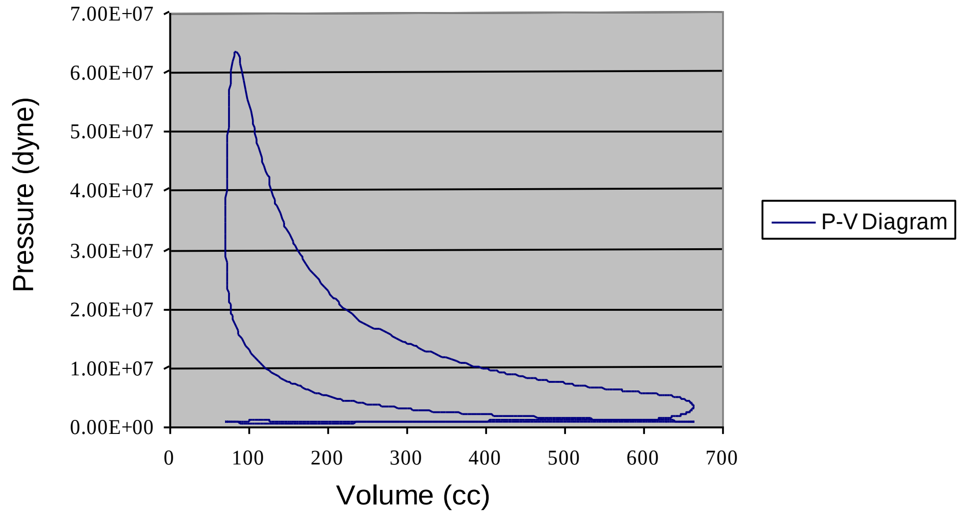

Figure 6. (P-V) diagram of improved Z24.

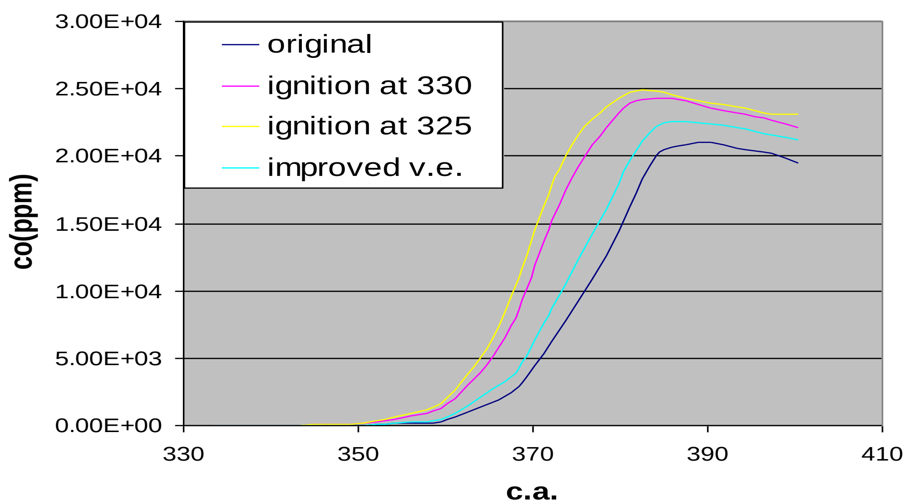

Figure 7. CO emission.

2. Consideration of the amount of emissions and compare it with original engine.
3. Consideration of probability of knock in this ignition timing.

Output power

Knowing the cylinder pressure in each crank angle and using the integral $\int_0^{720} PdV$, output power is driven. For this calculation, we use MATLAB by using traps () function. This function calculates the integral, numerically. So it calculates the area under the curve in (P-V) diagram. It is shown in Figure 6. Calculation shows us the output power increase almost 10.9%. It is shown in Table 6.

Emission

Here, we consider the emission's diagram. As shown in emission's figure, in state ignition timing, the emission CO and NOx have the maximum amount and in these tow cases, the amount of each emission increases according to increasing the advanced angle of ignition. The HC emission's behavior is completely reverse. According to increase the advanced angle of ignition, it decreases. So it has a good condition. As shown in Figure 8, the behavior of CO_2 is different from the other. The amount of this emission increases at first up to around 385° and then decreases according to increasing the advanced angle of ignition. As the advanced angle of ignition increases, the ignition process progresses better. We can confirm this claim with considering Figure 10, the

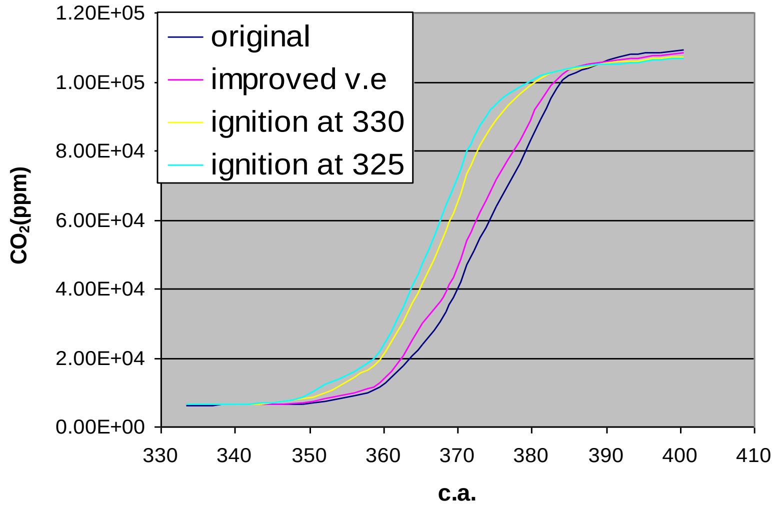

Figure 8. CO_2 emission.

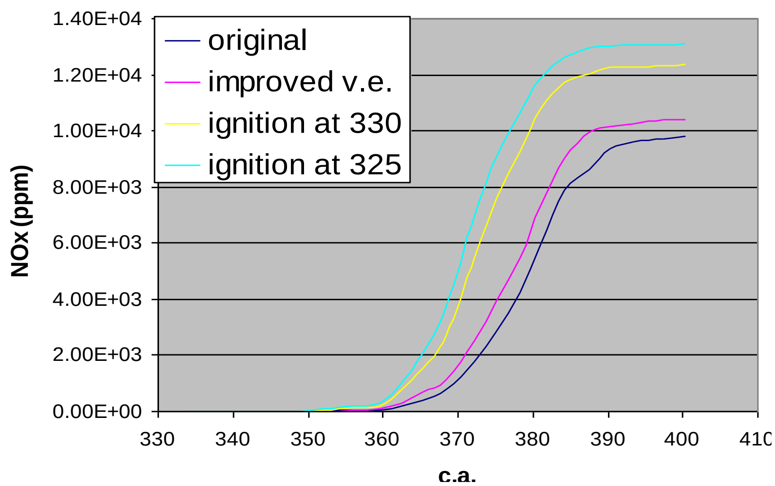

Figure 9. NOx emission.

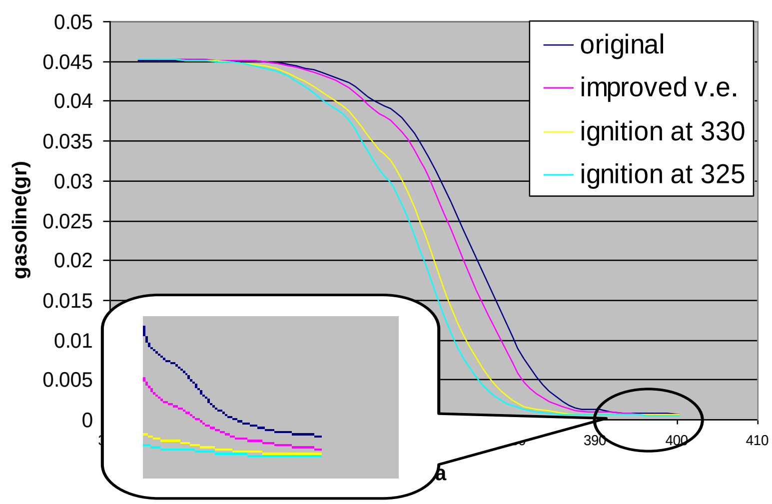

Figure 10. HC emission.

Table 6. Emission and power of Z24 in comparison with improved Z24 (Ø = 1).

Variables	Unit	Z24	Improved Z24(Ø =1)	Percentage of changes in comparison with original state (%)
Power	kw	52.77	57.52	10.90
CO_2	g	0.123	0.12	-2.50
	g/kw	0.00233	0.00208	-11
CO	g	0.0139	0.0169	12.10
	g/kw	2.63e-4	2.93e-4	11.10
NO	g	0.0075	0.01	13.30
	g/kw	1.42e-4	1.73e-4	12.10
Gasoline	g	7.07e-4	5.58e-4	-22.10
	g/kw	1.33e-5	9.76e-6	-28.10

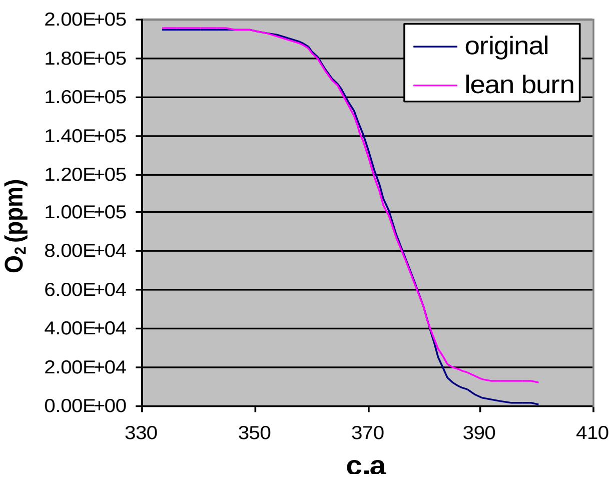

Figure 11. Consumption of O_2 in idle and lean mixture.

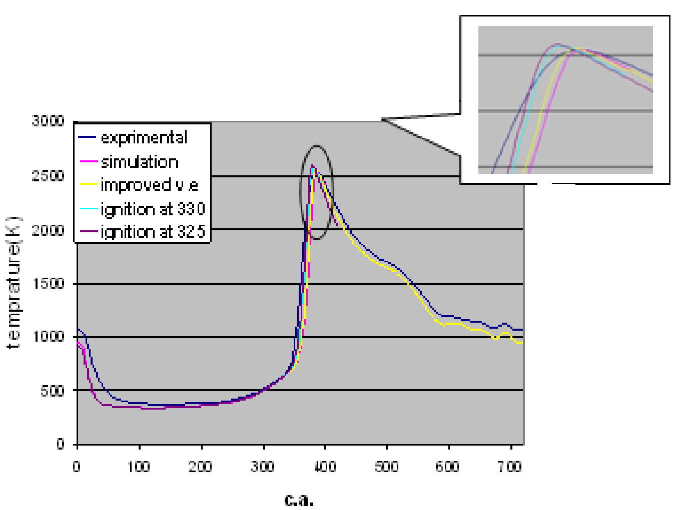

Figure 12. Temperature of combustion chamber in different ignition timing.

HC emission's behavior. As shown, it decreases according to increase in the advanced angle of ignition, so we can conclude that more fuel ignites more carbon molecules release in comparison with the other conditions. Consequently, the amount of CO increases. About CO_2, this theory is true until it is increasing. Decreasing the amount of CO_2 at the end of ignition process is because of shortage of O_2 in the combustion chamber. According to increasing the advance angle of ignition, the rate of ignition process and the amount of fuel that ignites, increases consequently the ignition confronts with more shortage of O_2, so there is not enough O_2 in the combustion chamber for oxidizing the CO and change it to CO_2. We can solve this problem with decreasing the amount of injected fuel. So our mixture becomes lean. This claim is confirmed with a new simulation. In this case, we simulated the ignition process in tow different air/fuel ratio Ø = 1 and Ø = 0.9. As shown in Figure 11, in the original state (Ø = 1). The ignition process encounters shortage of O_2 after around 385° and compensates this lack with this process:

$$CO_2 \Rightarrow CO + \frac{1}{2} O_2 \quad (2)$$

Consequently, the amount of CO_2 decreases and the amount of CO increases. But in the second state (Ø = 0.9), this problem is solved because there is a little excessive O_2 in the combustion chamber at the end of a combustion process. Increasing the amount of NOx is because of increasing the maximum temperature of the combustion chamber. As shown in Figure 12, increasing the advanced angle of ignition, the combustion chamber's temperature rises. Consequently, the amount of NOx that has a direct relationship with the maximum temperature of a combustion chamber rises. Figures 13 to 15 show the trend of amount of emissions in term of g/kW. The amount of HC emission decreases by almost 28%.

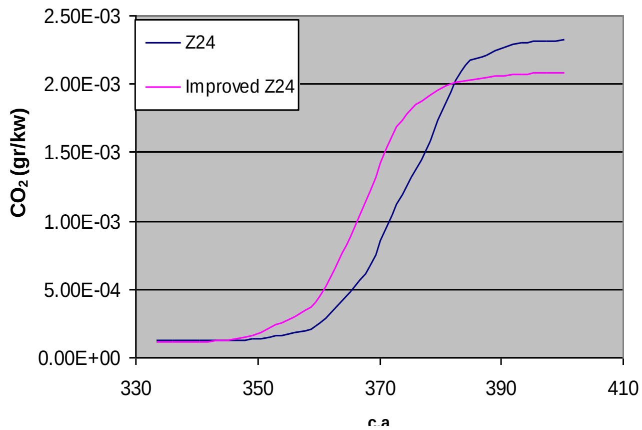

Figure 13. CO_2 emission.

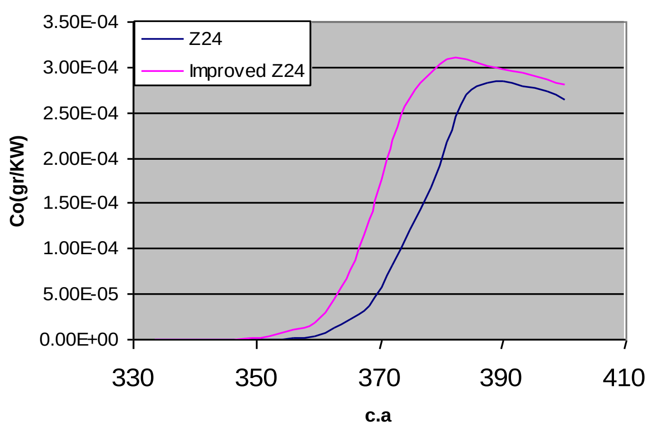

Figure 14. CO emission.

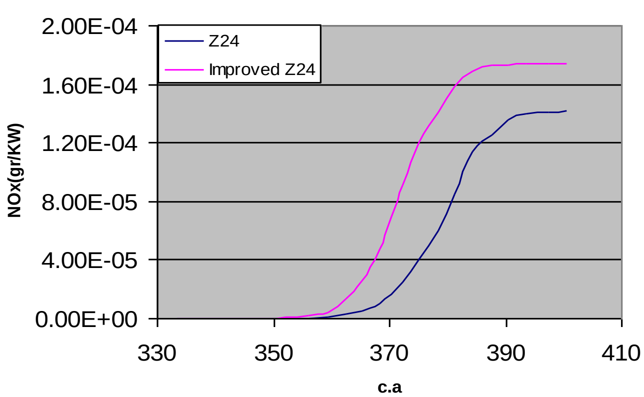

Figure 15. NOx emission.

In addition, the amount of emission decreases by almost 11%. However, the amount of CO and NOx decrease by 21 and 11%, respectively. Table 6 shows the results. As can be seen, our improved engine does not satisfy our aim in the amount of CO and NOx emission. So we decided to increase the air/fuel ratio to solve this problem.

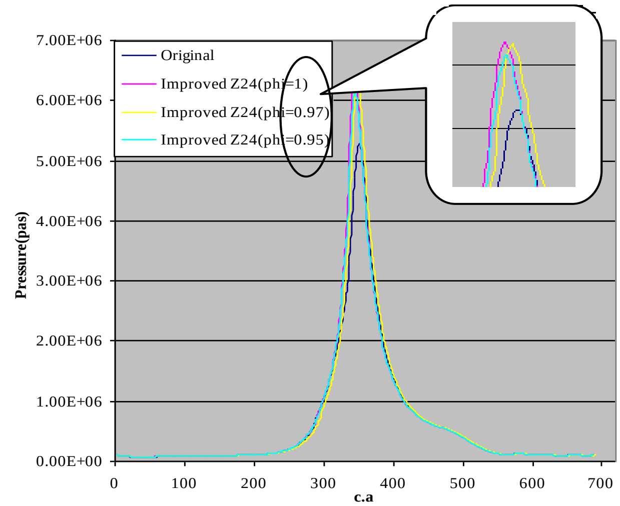

Figure 16. Pressure of combustion chamber in different air/fuel ratio.

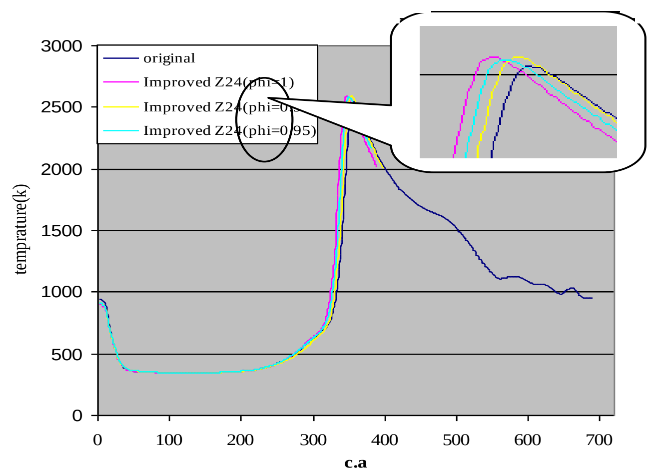

Figure 17. Temperature of combustion chamber in different air/fuel ratio.

As shown previously, by decreasing the amount of injected fuel, the ignition in the combustion chamber can compensate the shortage of O_2. Moreover, it should be noticed that decreasing the amount of injected fuel may lead to increase in the amount of NOx emission, so we should consider the entire situation, do this new simulation and then choose the best specification.

In this step, we did the simulation in tow air/fuel ratio, Ø = 0.97 and Ø = 0.95. When we decrease the amount of injected fuel poured into the combustion chamber, output power of engine decreases but in these tow conditions it is negligible, also the emission is very important. Consequently, this decrease can be ignored. The results are shown in Figures 16 to 20. According to these figures, we conclude the state is the best because the output power is almost constant and the CO, CO_2 and HC

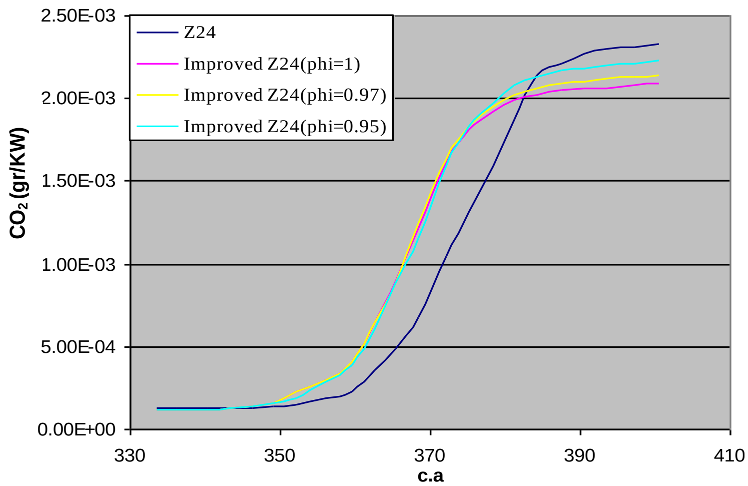

Figure 18. CO_2 emission in different air/fuel ratio.

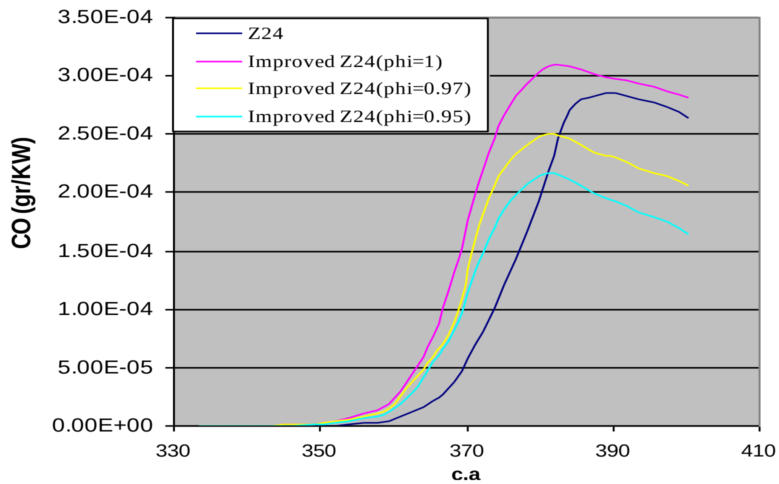

Figure 19. CO emission in different air/fuel ratio.

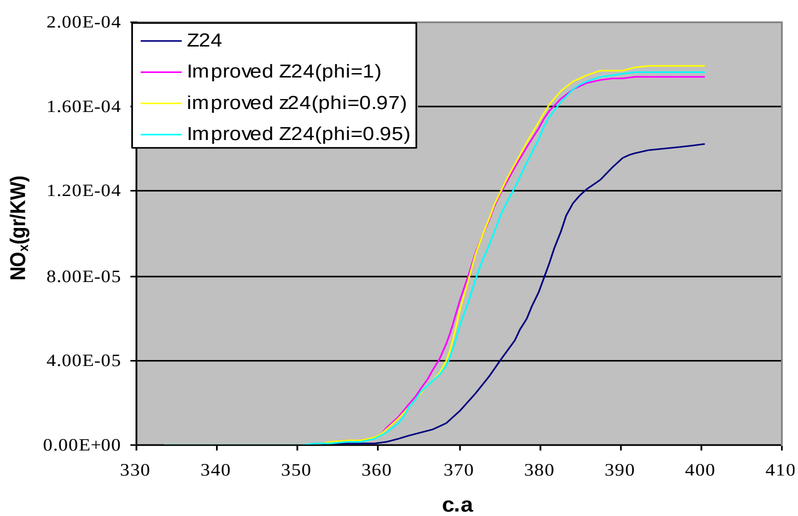

Figure 20. NOx emission in different air/fuel ratio.

Table 7. Emission and power of Z24 in comparison with improved Z24 (Ø = 1)

Parameter	Unit	Z24	Improved Z24 (Ø = 0.97)	Percentage of changes in comparison with original state (%)
Power	kw	52.77	57.12	10.82
CO_2	g	0.123	0.123	0
	g/kw	0.00233	0.00215	-8
CO	g	0.0139	0.0119	-15.10
	g/kw	2.63e-4	2.06e-4	-22.70
NO	g	0.0075	0.0103	13.70
	g/kw	1.42 e-4	1.80e-4	12.60
Gasoline	g	7.07e-4	4.48e-4	-36.70

Table 8. Specification of improved Z24.

Quantity	Specification
35°	Ignition timing
250°	Injection timing
238°	During injection
44.135 mg	Mass of injected fuel (g/cycle)

Table 9. Improved Z24 engine valve timing.

IVO	12 c.a BTDC
IVC	35 c.a ABDC
EVO	43 c.a BBDC
EVC	3 c.a ATDC

emissions decrease. Of course, the trend of NOx emission is diverse but its amount decreases negligibly in comparison with previous state. All the results are shown in Table 7. Finally improved Z24 with these specifications is derived Table 8. To fix these specifications, we must examine the probability of knock.

Conclusion

In this work, NISSAN Z24 engine was simulated numerically to investigate the effects of valves and ignition timings and also modifying them to improve the engine performance and reducing the emissions Table 9. It has been concluded that: (a) By changing and improving the intake and exhaust valve timing and ignition timing, the engine performance (output power and emission) gets better; (b) The HC emission decreases by increasing the advanced angle of ignition; (c) The CO and CO_2 emission decreases by decreasing the air/fuel ratio, and (d) The NOx emission increases by increasing the advanced angle of ignition as increasing the advanced angle of ignition leads to increasing the combustion chamber temperature.

REFERENCES

Boyce BP, JK Martin, Poehlman AG, Shears D (1999). Effects of Ignition Timing and Air-Fuel Ratio on In-Cylinder Heat Flux and Temperatures in a Four-Stroke, Homogeneous Charge Engine, International Congress and Exposition, Detroit, MI, USA.

Duclos JM, Bruneaux G, Baritaud TA (1996). 3D Modeling of Combustion and Pollutants in a 4-Valve SI Engine; Effect of Fuel and Residuals Distribution and Spark location, SAE Technical Paper #961964.

Eckert P, Kong SC, Reitz RD (2003). Modelling Autoignition and Engine Knock Under Spark Ignition Conditions", SAE World Congress and Exhibition, Detroit, MI, USA.

Ferguson CR, Kirkpatrick AT (2001). Internal Combustion Engines, Applied Thermodynamics (2nd ed) Wiley.

Heywood JB (1988). Internal Combustion Engine Fundamentals", McGraw-Hill Inc.

Pulkrabeck WW (2003). Engineering Fundamental of Internal Combustion Engine (2nd ed), Prentice Hall.

Shayler PJ (2007). Experimental Investigations of Intake and Exhaust Valve Timing Effects on Charge Dilution by Residuals, Fuel Consumption and Emissions, SAE World Congress and Exhibition, April.

Siewert RM (1971). How Valve Timing Events Affect Exhaust Emissions, General Motors Corp, SAE Technical Papers #710609.

Smith JR, Green RM, CK WestBrook, Pitz WJ (1984). An Exprimental and Modeling Study of Engin Knock," Twentieth Symposium on Combustion Institute, Pittsburgh, PA.

Tuttle JH (1980). Controlling Engine Load by Means of Late Intake Valve Closing, SAE paper #800794.

Tuttle JH (1982). Controlling Engine Load by means of Early Intake-Valve Closing, SAE paper # 820408.

Zhu GG, Haskara I, Winkelman J, Corp V (2004). IC Engine Retard Ignition Timing Limit Detection and Control Using In-Cylinder Ionization Signal, Powertrain and Fluid Systems Conference and Exhibition, Tampa, FL, USA.