Iran University of Science and Technology

International Journal of Automotive Engineering

Journal Homepage: ijae.iust.ac.ir

ISSN: 2008-9899

Numerical investigation of the variation of compression ratio on performance and exhaust emission of a turbo-diesel engine

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ARTICLE INFO

Article history:

Received : 30 June 2019

Accepted: 28 Aug 2019

Published:1 Sept , 2019

Keywords:

Numerical solution,
engine performance,
Diesel engine,
compression ratio,
Turbocharger

A B S T R A C T

Changing the compression ratio and presence of turbocharger are two important issues, affecting on performance, and exhaust emissions in internal combustion engines. To study the functional properties and exhaust emissions in regards to compression ratio at different speeds, the numerical solution of the governing equations on the fluid flow inside the combustion chamber and the numerical solution of one-dimensional computational fluid dynamics with the GT-Power software carried out. The diesel engine was with a displacement of 6.4 Lit and Turbocharged six cylinder. In this engine was chosen, the compression ratio between 15: 1 and 19: 1 with intervals of one unit and the range of engine speed was from 800 to 2400 rpm. The results showed that by the presence of a turbocharger and changing the compression ratio from 17: 1 to 19: 1, the braking power and torque increased by about 56.24% compared to the non-turbocharged engine. In addition, was reduced the brake specific fuel consumption due to higher power output. The amount of CO and HC emissions decreases based on the reduction of the compression ratio compared to the based case, and the NOX value increases due to the production of higher heat than turbocharged engines. The overall results showed that the turbocharged engine with a 19: 1 compression ratio has the best performance and pollution characteristics.

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DOI: 10.22068/ijae.9.3.2991

1 Introduction

Nowadays, due to growing demand for energy resources, the reduction of fossil fuel resources, the need to maintain the environment, reducing air pollution, fuel supply limits, optimum use of fuels and increase the power output of diesel engines, Research in this field has become inevitable. One of the biggest problems in big cities is the exhaust emissions of vehicles. The use of inappropriate fuels in diesel vehicles increases the mortality rate and growth of lung cancer due to car exhaust emissions. With regard to the above, it can be concluded that fossil fuels, despite the low mining costs, It puts a lot of costs on the health of the community and the environment. Therefore, the solution to overcome this crisis is to reduce the sources of pollutants from the origin of production of these pollutants.

In internal combustion engines, the compression ratio and turbocharger presence are two important factors and affecting on engine capabilities and pollutant characteristics. In a few studies, researchers investigated the effect of compression ratio on the performance and emission characteristics of diesel fuel mixed with ethanol in a DI compression ignition engine. The experimental results showed that by increasing the compression ratio for all the mixtures, the brake thermal efficiency decreased and the brake specific fuel consumption decreased. The results also indicated that the BSFC with mixed fuels increased. In addition, when the compression ratio increased from 15 to 19, HC and CO emissions strictly decreased and NOX emissions significantly increased [1-3].

In a diesel engine with the variable compression ratio and alcoholic fuels, increasing the compression ratio leads to an increase in NOx and CO2 emissions. Added alcohol to diesel fuel reduces significantly the brake thermal efficiency so that the specific fuel consumption increase [4]. In an experimental study, the effect of compression ratio on the performance and emissions of a spark ignition engine with a mixture of gasoline and butanol was investigated in different loads. The results showed that brake thermal efficiency increased with increasing compression ratio at all loads [6, 7].

The other researcher [8, 9], was investigated variation of compression ratio on the braking power in a gasoline single-cylinder engine. In these studies, the effect of compression ratio and throttle position on the braking power was investigated. The results showed that the compression ratio of 9.3:1 and throttle position with 75% fully opens the valve produces the highest braking power. The researchers studied the effect of compression ratio on the performance and exhaust emission a spark-ignition engine with direct injection of ethanol fuel. By decreasing compression ratio with methanol fuel, torque and engine power reduced by more than 3.5%, and its thermal efficiency in the low load is increased by 18 %. Reducing the compression ratio can significantly reduce the maximum rise in the maximum pressure and improve the brake thermal efficiency at the low loads. Moreover, HC and NO emissions with methanol fuel engine increase when compression ratio goes up, but CO emission is inverse [10].

In a DI engine showed that compression ratio effect on combustion and exhaust emissions and adding butanol and ethanol to gasoline was effective in raising the MFB50 point and reducing the combustion duration. In addition to gasoline, butanol is also effective in reducing exhaust emissions, while reducing NOX is the main advantage of ethanol fuel. Also, the results showed that the co-integration between the compression ratio and added alcohol to gasoline allowed gas control with the improvement of fuel economy simultaneously [11, 12]. In another study, the effect of changing the compression ratio and combination of palm oil and diesel fuel on engine performance and exhaust gases was investigated. The results demonstrated that the BSFC and the thermal efficiency decreased, while the amount of NOX increased when the engine was powered by diesel fuel [13-15].

Also, the results of Karabektas et al & Hossain et al. in a four-stroke diesel engine with the variable compression ratio in the range of 16: 1 to 20: 1 on the engine performance showed that by increasing the compression ratio, exhaust gases temperature, torque and motor braking power, the engine volume efficiency and specific fuel consumption decreases [16,17].

Other factors such as variable ignition variable timing and injection timing as well as the use of different fuels in a gasoline direct injection engine showed that it had a great impact on the performance of the engine and the exhaust

[DOI: 10.22068/ijae.9.3.2991]

gases and caused that engine performance improved and reduced exhaust emissions[18,19]. Other studies also found that increasing the oxygen content in the bioethanol-gasoline blend reduced the exhaust emissions by 163% and fuel consumption by about 16%. Meanwhile, other pollutants such as CO and HC are reduced [20, 21].

The use of rice bran biodiesel - the biological fuel of a diesel engine with the variable compression ratio in full load showed that the maximum brake thermal efficiency decreases with decreasing the compression ratio. On average, CO emission and HC increased with increasing compression ratio And NOx and CO2 increase [22]. Also, the effects of the distillate fuel (diesel, biodiesel, and ethanol) on emissions from diesel engines proved that hydrocarbon gases have been cut by about 10 percent and carbon dioxide has increased by about 7 percent. In general, the results showed that the use of the D91B6E3 fuel mixture could have the best efficiency, performance and lowest pollutants [23, 24].

In a study, researchers simulated the existence of a turbocharger on pollutant levels of a motor. The results showed that NOx, CO and CO2 emissions in turbocharger engine are higher than without turbocharged engine. However, it can be said that at the same time, the turbocharged engine produces higher brake power and lower pollutant. [25] In another study, the effect of the turbocharger on the parameters of engine fuel consumption, power and traction The ITM475, ITM485 and ITM800 tractors showed that the specific fuel consumption of turbocharged tractors ITM485 and ITM800 is lower than that of an ITM475 turbocharged tractor. The amount of power and traction strength in turbocharger tractors is significantly higher than that of a tractor without turbocharged [26-28].

Therefore, the goal of this research is to investigate the effects of variations the compression ratio of a turbocharged diesel engine on performance and exhaust characteristics using the GT POWER software in full load conditions and at minimum and maximum engine speeds.

2 Materials and methods

The research engine in this study is a six-cylinder direct injection diesel engine John Deere 6068HF275. The engine characteristics are shown in Table 1.

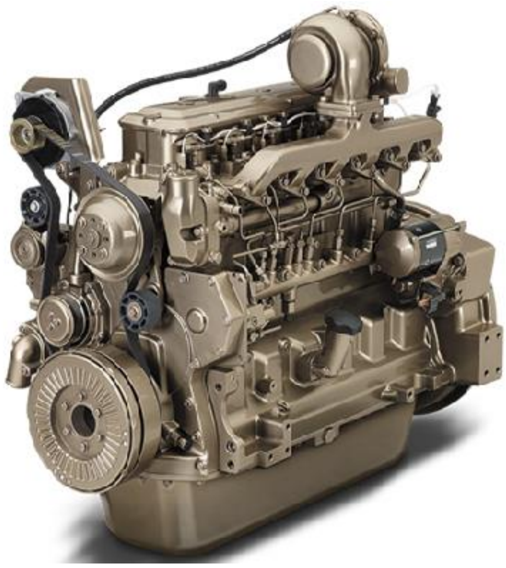

Figure 1. John Deere engine

Table 1. the engine specifications of John Deere 6068HF275

Engine characteristics	Value
Displacement	6.8 L
Number of cylinders	6
Cylinder bore	106 mm
Stroke	127 mm
Connecting rod length	270 mm
Standard injection timing	4 BTDC
Compression ratio	17:1
Maximum torque	740-930 N.m @ 1400 RPM
Maximum power	129-187 kW @ 2000-2400 RPM

2.1 simulation and modeling

In this study, the six-cylinder engine shown in Figure 1 is modeled and simulated by the GT-Power software to examine the effect of the compression ratio and turbocharger on the engine performance. To do this research, all parts of the engine were initially introduced into the software, like a real six-cylinder engine, and then required data based on actual engine conditions at the atmospheric pressure of 1 atm. Meanwhile, the injection mass in each engine cycle of 96 milligrams and the length of the injection rate of 20 degrees has

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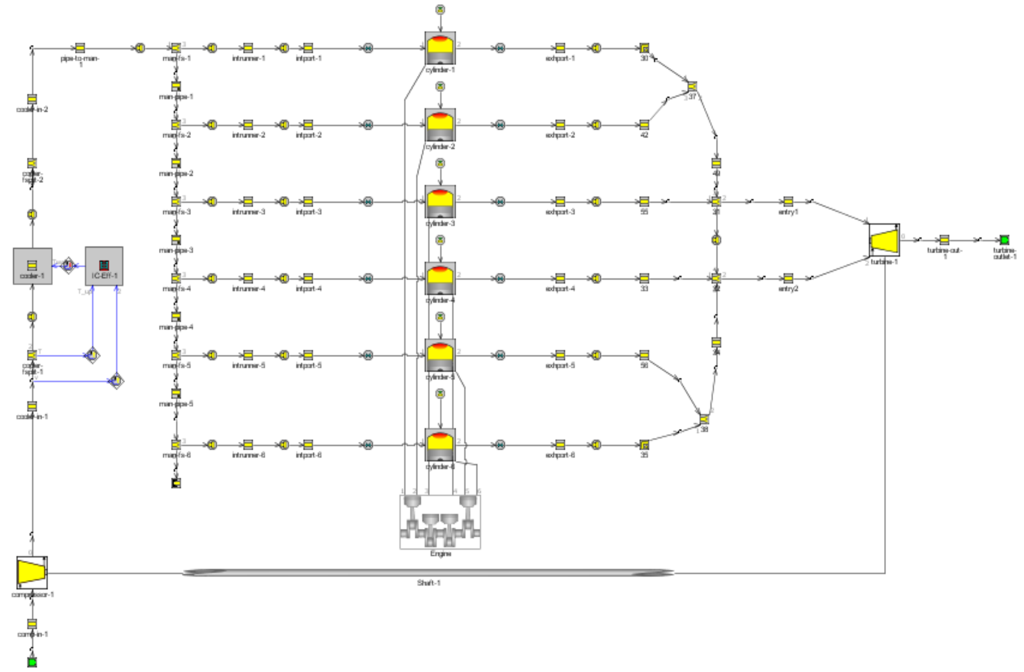
been selected and the engine speed has changed from 800 to 2400 rpm, and advanced injection timing was considered 2 degrees for each 200 rpm increment.

GT-Power software is part of the GT-Suite software and gamma Technology Company. This software simulates the engine and its accessories. The numerical solution in this software is based on solving one-dimensional fluid dynamics equations including phenomena related to flow motion, heat transfer in the manifold, combustion chamber and other components of the engine. Fig 2. Show the computational model of a direct injecting (DI) turbocharged diesel engine with six-cylinder by Gt-POWER software.



The computational model of a direct injection turbocharged diesel engine with six-cylinder

2.2 Fluid Dynamics Governing Equations

The flow model involves the solution of the Navier-Stokes equations, namely the conservation of continuity, momentum and energy equations. Which are calculated according to formulas 1 to 4. In the GT-Power software, the below equations are computed in a one-dimensional model. This shows that all the equations are in the way of the averaging. In this study, explicit solving was used to solve the equations, in which base variables are explicitly solved in mass flow, density, and internal energy. In explicit solving, the system is divided into small volumes, in which all the splitters are subdivided into a sub volume and all tubes of one volume or more. The scalar variables (pressure, temperature, density, internal energy, enthalpy, etc.) are assumed to be uniform on the boundary of each of the underlying volumes. Vector variables (mass flux, velocity, mass fraction flux, etc.) are calculated for each boundary.

$$\frac{dm}{dt} = \sum_{boundaries} \dot{m} \quad (1)$$

$$\frac{dme}{dt} = -P\frac{dV}{dt} + \sum_{boundaries} \dot{m}H - hA_s(T_{fluid} - T_{wall}) \quad (2)$$

$$\frac{d\rho HV}{dt} = +V\frac{dp}{dt} + \sum_{boundaries} \dot{m}H - hA_s(T_{fluid} - T_{wall}) \quad (3)$$

$$\frac{d\dot{m}}{dt} = \frac{dpA + \sum_{voundaries} \dot{m}u - 4C_f \frac{\rho u|u|}{2}\frac{dxA}{D} - C_p\left(\frac{1}{2}\rho u|u|\right)A}{dx}$$

[DOI: 10.22068/ijae.9.3.2991]

Where $m^{\cdot}$ is Mass flow rate, m =mass, V =volume, p= pressure, ρ =density, A =cross-sectional area, A_s = the heat transfer area, e= is the total energy and H is enthalpy.

2.3 Fluid Properties

In the process of engine simulation, diesel fuel was used. The GT-Suite software library contains many types of fluids and their specifications and features. In addition to introducing uncompressible fuel specifications, the software also needs to include fuel vapor characteristics, so that in case of evaporation, fluid specifications are predictable. The important properties of the fuel used is shown in Table 2.

Table 2. some properties of diesel fuel

fuel properties	unit	Diesel
Density	$m\ s^{-1}$	830
Heat vaporization at 298k	Mj	0.25
Oxygen Atoms per Molecule	…	0
Hydrogen Atoms per Molecule	…	23.6
Carbon Atoms per Molecule	…	13.5
Lower Heating Value	Mj	43.25
Critical Temperature	k	569.4
Critical Pressure	bar	24.6

3 Results and Discussion

3.4 Brake power and brake torque

The variation of brake torque and power versus engine speed are shown in Figures 3 and 4 in turbocharged and the naturally aspirated engine. Figures 3 and 4 show that increase of compression ratio in a turbocharged engine leads to increase of braking power and torque due to the improvement of combustion. The maximum increment of brake power and torque in a turbocharged engine was 24.56% at the compression ratio of 19:1 as compared to baseline engine and its lowest was equal to 12.2% at the compression ratio of 15: 1 with the naturally aspirated engine.

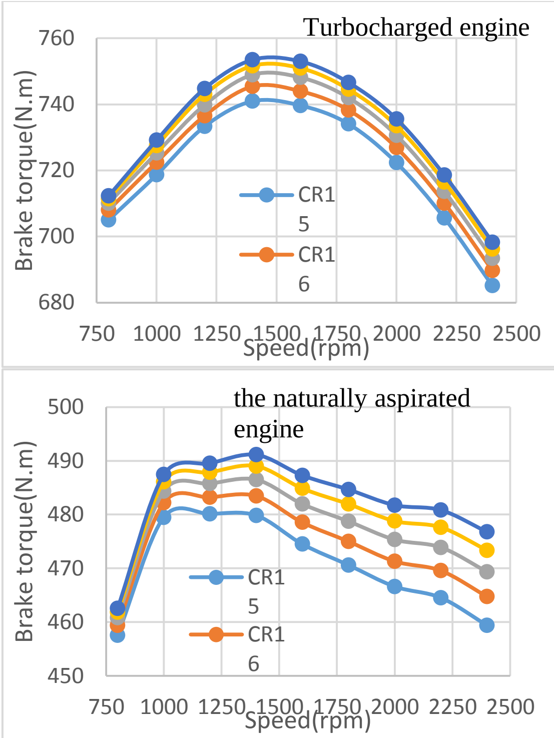


Figure 2. Brake torque versus engine speed in turbocharged and the naturally aspirated engine at different compression ratio

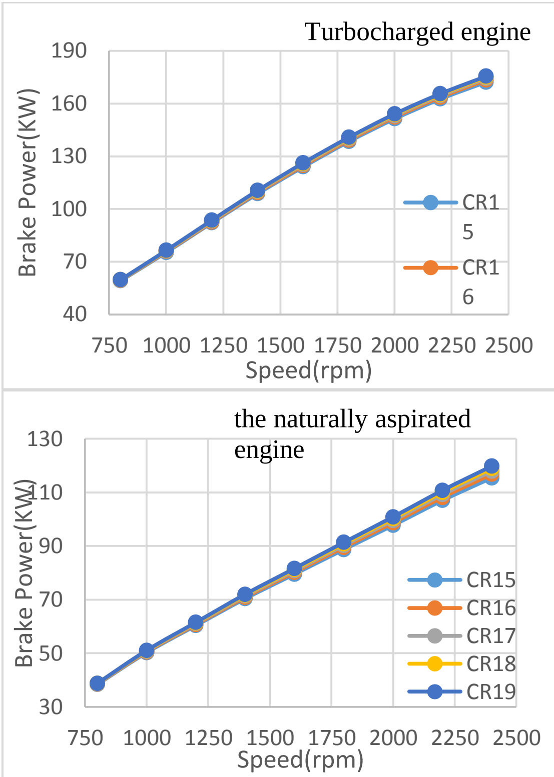


Figure 3. Brake power versus engine speed in turbocharged and the naturally aspirated engine at different compression ratio

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3.5 Brake Specific Fuel Consumption (BSFC)

BSFC is defined as the ratio of burnt fuel to the power output. As shown in Fig. 5, with the increase in the compression ratio, the brake specific fuel consumption decreases due to higher power generation ratio to the fuel used in the engine. In this research, in turbocharged engine, the brake special fuel consumption was 35/99% lower with the compression ratio of 19:1 and in the naturally aspirated engine, the brake special fuel consumption was 2/17% greater in a compression ratio of 15:1 in comparison to the baseline.

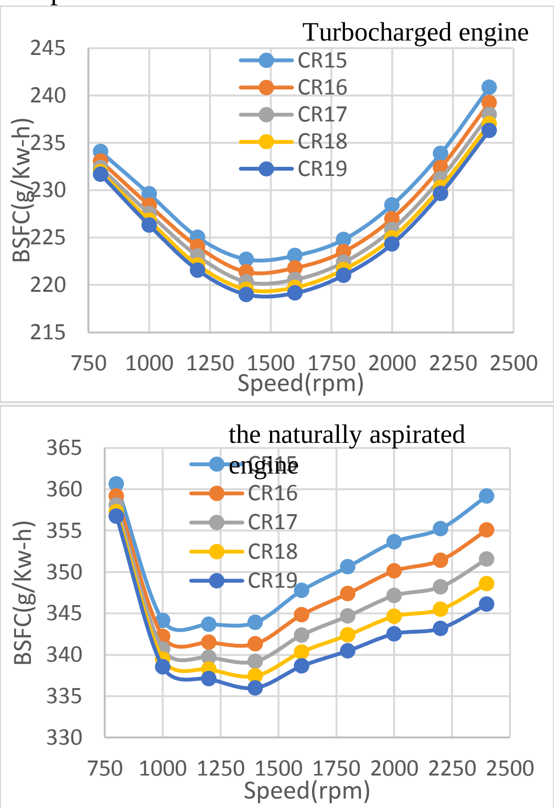

Figure 4. Brake specific fuel consumption versus engine speed in turbocharged and the naturally aspirated engine at different compression ratio

3.6 Exhaust gases temperature

The temperature of the exhaust gas decreases with increasing compression ratio, because of the burn rate increases with increasing compression ratio and decreases the time interval for full combustion, which this is lead to reduce the gas outlet temperature. According to Fig. 6, the outlet gas temperature in the turbocharged engine is greater than the gas outlet temperature in a the naturally aspirated engine, and the highest outlet temperature at the compression ratio of 15:1 is 15.54% as compared to baseline in the turbocharged engine and the lowest output temperature was obtained at the compression ratio of 19:1 With a 0.28% lower compared to natural breathing engine at baseline case.

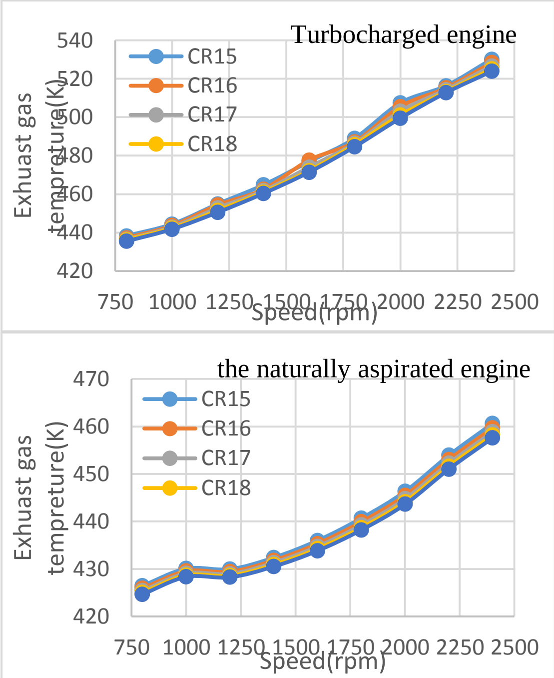

Figure 5. Exhaust gas temperature versus engine speed in turbocharged and natural breathing engine at different compression ratio

3.7 pressure inside the cylinder

Increasing the compression ratio results in better fuel mixing and higher temperatures during compression. The increase in compression ratio is expected to increase cylinder pressure. As shown in Fig. 7, the maximum cylinder pressure at the compression ratio of 19:1 in the turbocharged engine and the lowest pressure in the compression ratio of 15:1 was created in the naturally aspirated engine.

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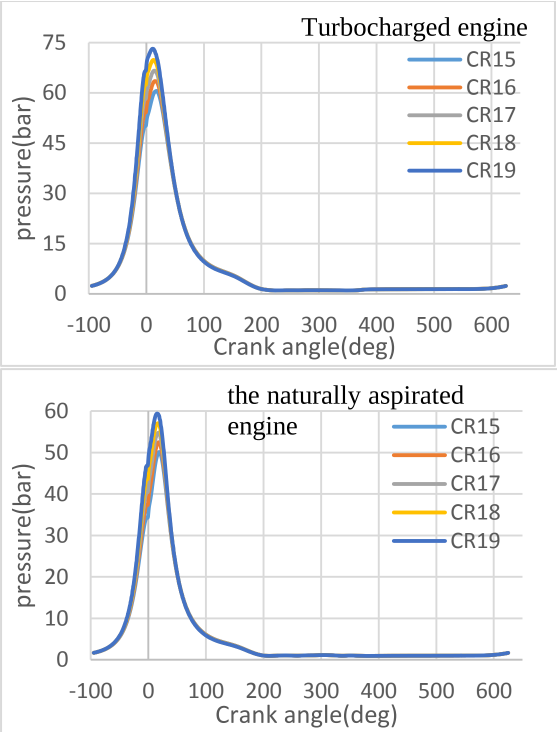

Figure 6. the cylinder Pressure versus crank angle in turbocharged and the natural breathing engine at different compression ratio

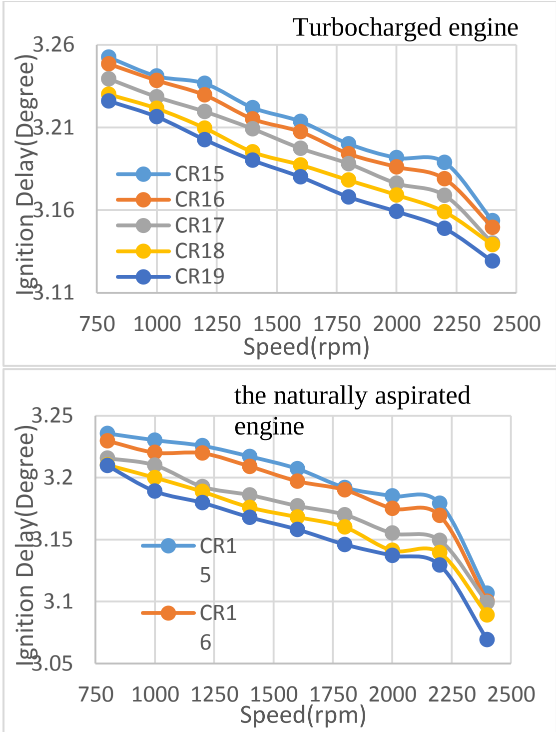

Figure 7. Ignition delay versus engine speed in turbocharged and the naturally aspirated engine at different compression ratio

3.8 Ignition delay

Many operating and design factors such as compression ratio, output, inlet temperature, engine speed, fuel injection pressure, air to fuel ratio, cetane number and fuel atomization effect on the ignition delay. Increasing the compression ratio increases the compressed temperature and also reduces the minimum flammable temperature by reducing the ignition delay. This may be due to increased compressed air density and the interaction between oxygen molecules and fuel. According to Fig. 8, due to the presence of a turbocharger and more oxygen and combining it with fuel, the highest ignition delay was happening 76.1% higher than the turbocharged engine.

3.9 Exhaust emissions

The emission of CO and HC from the engine mainly depends on the fuel's properties, the availability of oxygen and it mixture with fuel and also temperature and turbulence inside in the combustion chamber. According to Figs. 9 and 10, the CO and HC emissions increase with the increase of compression ratio. Complete combustion and fuel burning lead to reduction CO and HC emissions [29]. The use of a turbocharger increases air intake to a diesel engine, and fuel and air can be easily mixed in the combustion chamber, resulting in complete combustion and lower CO and HC emissions. Fig. 11, Shown the variation CO_2 versus engine speed at different compression ratio. The greater amount of CO_2 represents the full combustion of fuel in the combustion chamber. Therefore in a turbocharged engine, due to the existence of sufficient oxygen and complete combustion, has a higher CO_2 emission than a natural breathing engine. The amount of CO_2 emissions in a turbocharged engine increases with increasing compression ratios and in a naturally aspirated engine decrease with increasing the compression ratio.

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CO_2 emission isn't very harmful to humans, but it has a strong potential for ozone depletion and global warming [30]. The thermal mechanism of fuel, combustion temperature, oxygen content and the long-term presence of gas are the most important factors in the formation of NOx. With respect to Fig. 12, the amount of NOx is reduced by increasing the compression ratio in the turbocharged engine, and the amount of NOX in the natural breathing engine increases. As it is clear, the amount of oxygen is directly related to the release of NOX. NOX emission in the turbocharged engine is higher due to increased oxygen in fuel than a naturally aspirated engine.

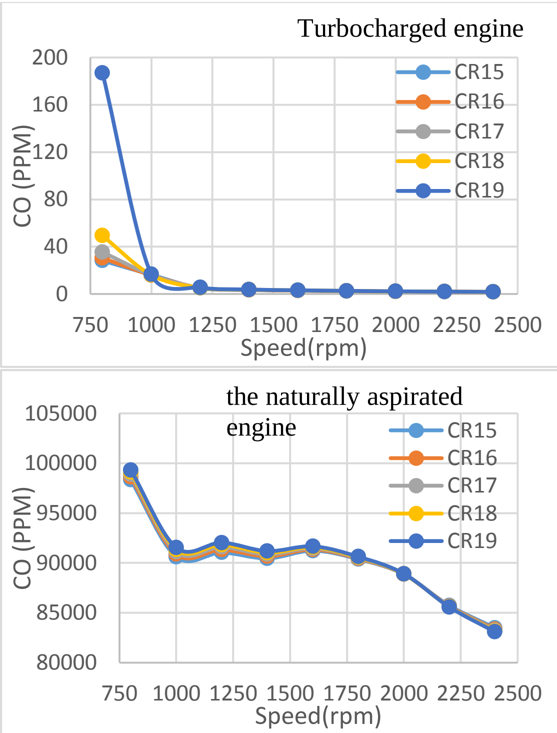

Figure 8. CO emission versus engine speed in turbocharged and the natural breathing engine at different compression ratio

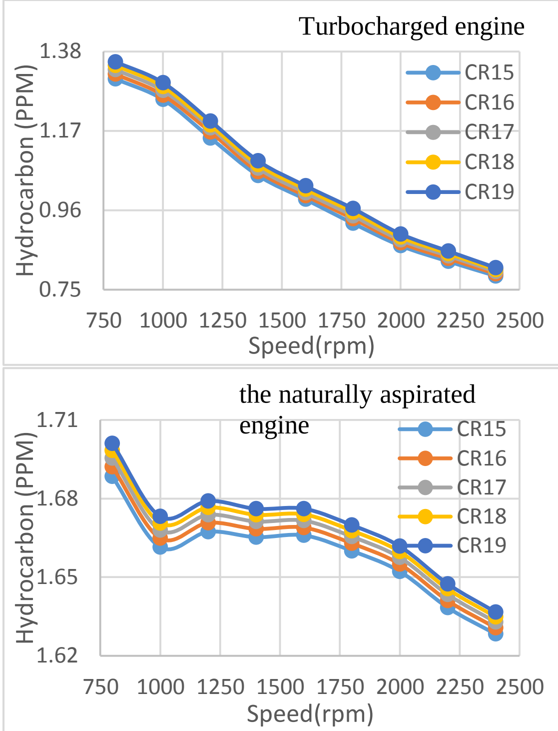

Figure 9. HC emission versus engine speed in turbocharged and the natural breathing engine at different compression ratio

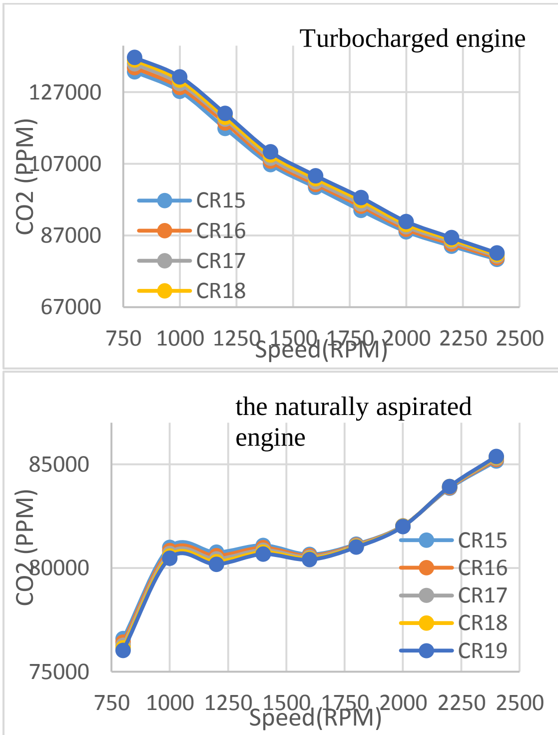

Figure 10. CO2 emission versus engine speed in turbocharged and the natural breathing engine at different compression ratio

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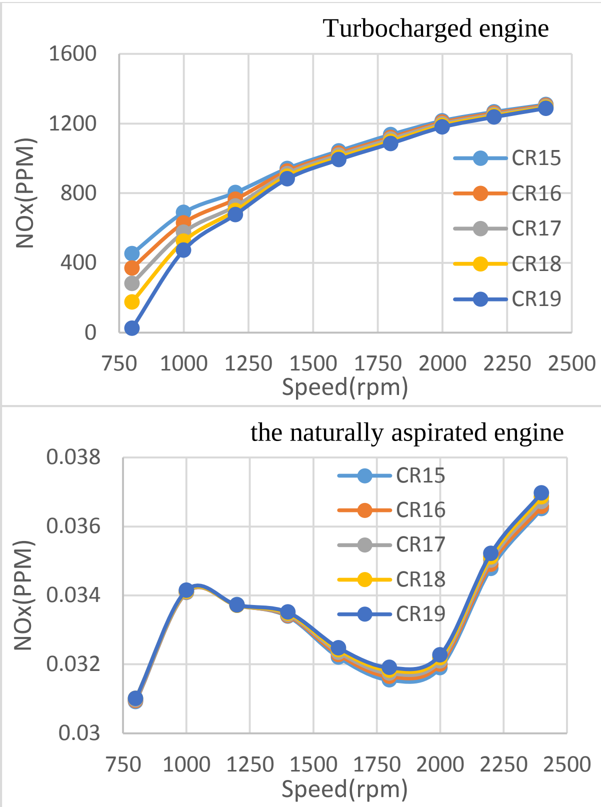

Figure 11. NOX emission versus engine speed in turbocharged and the natural breathing engine at different compression ratio

4 Conclusions

In this research, the performance and emissions of a naturally aspirated and turbocharged six-cylinder engine with regard to different compression ratio were studied, in which the following results were obtained:

- The power and torque values are increased about 56.24% at the compression ratio 19:1 as compared to baseline in a turbocharged engine.
- With increasing compression ratio in a turbocharged engine with a compression ratio 19: 1, the brake specific fuel consumption is reduced about 35/99% compared to baseline engine.
- As the compression ratio increase, CO, and HC emissions increased and NOX emissions decreased in the turbocharged engine but in the naturally aspirated engine increased.
- The results showed that Turbocharger improves engine performance and reduces emissions of hydrocarbons and carbon monoxide.
- In overall, the results showed that turbocharged engine with the compression ratio of 19: 1 has the highest performance and the lowest emissions in this study.

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