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Effect of double gasket on combustion characteristic, performance and emissions of GDI engine

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Abstract. In this article, the effect of adding a double gasket to cylinder head on combustion characteristics, performance and exhaust gas emissions of gasoline direct injection GDI engine was numerically investigated by utilizing the BOOST program. The study was carried out at different engine speed (1000 rpm to 3500 rpm, with increment 500 rpm) in a constant engine load fueled with gasoline fuel. The Vibe two-zone and Woschni 1990 models were selected as sub-model to calculated the combustion and heat transfer. The numerical results showed that the engine with a double gasket produces lower effective power and lower effective torque while the brake-specific fuel consumption BSFC was higher compared to that of an engine with a single gasket (original). Regarding the exhaust gas emissions, the engine with a double gasket emitted lower NOx emissions, while the soot emission was higher than that of the engine with a single gasket. Keywords: Engine Performance, Emissions, GDI engine.

1. Introduction
Recently, there is considerable effort spent by researchers to invented a suitable alternative fuel that can be used for internal combustion engines or developed new technology that could be applied for the engine to improve efficiency and reduces toxic emissions [1-4]. Gasoline direct injection (GDI) is new technology recently wide using in spark-ignition engines where the gasoline fuel directly injected into the combustion chamber this can be considered as a perfect solution to produces engines with higher performance and lower emissions [5]. In 1925s the first GDI engine system was produced and used in the truck with a lower compression engine. In the 1950s, the Bosch mechanical GDI system was utilized in several German passenger vehicles [6]. The GDI fuel injection technology type stayed rare until 1996 when the Mitsubishi car company decided to use the electronic GDI as an official system in the production car line. After that, the GDI engines have widely used by the automotive industry especially in the USA to reach approximately 50% of the vehicle models produced in the year 2016 [7-10]. There are some obstacles and problems associated with the use of this type of engine, which required to do different studies during the last decades to avoid these issues and to develop this system type. Karaya and Mallikarjuna [11] numerically investigated the effect of four-piston profiles (flat piston with offset bowl (FPOB), offset pentroof with offset bowl (OPOB), inclined piston with offset bowl (IPOB), offset pentroof with offset scoop (OPOS) on GDI engine performance and emissions. The study results were collected at an engine speed of 2000 rpm and equivalence ratio of 0.65±0.05 and appeared that OPOB

piston gave better indicated mean effective pressure, in-cylinder flow and emitted lower unburnt hydrocarbon than that of other selected pistons types. Wei et al [12] experimentally examined the effect of the olefin content on the emissions and performance of the GDI engine at different engine speeds and various loads. The results showed that carbon monoxide emission decreases by 22.8%, the carbon dioxide emission increases up to 5% when the olefin content decreased, while no noticeable effect on engine effective power was observed when changed in the olefin content.

In the last decade, there is wide use of the GDI engine type with passenger cars (Kia and Hyundai) in Iraq, as known this type of engine consumed lower fuel quantity to produces high performance with lower emissions [13-15]. This kind of engine required a high fuel quality (pure with high octane number more than 91), otherwise, the GDI engine showed a big problem especially in summer (average temperature above 45 $^{\circ}$C) due to the detonation (knocking). Unfortunately, in Iraq, gasoline fuel has poor quality (octane number less than 87). To solve this issue there are two methods that can be used either using fuel with high quality this means double in the cost than the other fuel or utilizing a double gasket to head engine (local method).

Therefore, the aim of this work is to show the effect of adding a double gasket to the cylinder head on combustion, performance and emissions of a GDI engine at different engine speeds and constant load operating by gasoline fuel.

2. Simulation Procedures

In this work, the AVL WORKSPACE which considers one of the best programs used to investigate the internal combustion engine efficiency for different engines at altered operating conditions. This program provides several options related to fuel such as diesel, gasoline, hydrogen, ethanol, propane, methane. Here, the GDI engine model was built in AVL BOOST 2016 simulation code to estimate the engine performance, combustion and emissions at different engine speeds and constant load with single and double gasket. Initially, the model was calibrated for the combustion chamber process based on the AVL documentation (AVL BOOST theory and users guide v2016) [16] and then adjusted according to the model results to reach a good agreement with experimental data. The engine components such as system boundaries, air filter, intake manifolds, cylinder geometry, exhaust pipe, catalyst geometry were taken based on the test engine dimensional and linked together in the program interface by pipes as shown in figure 1. The start of fuel injection, the air mass flow, the rate of fuel injection and the fuel mass flow rate were measured experimentally and implement into the programming before it running. The Vibe two-zone combustion model and the Woschni 1990 heat transfer model were selected. The main engine details have been presented in Table 1.
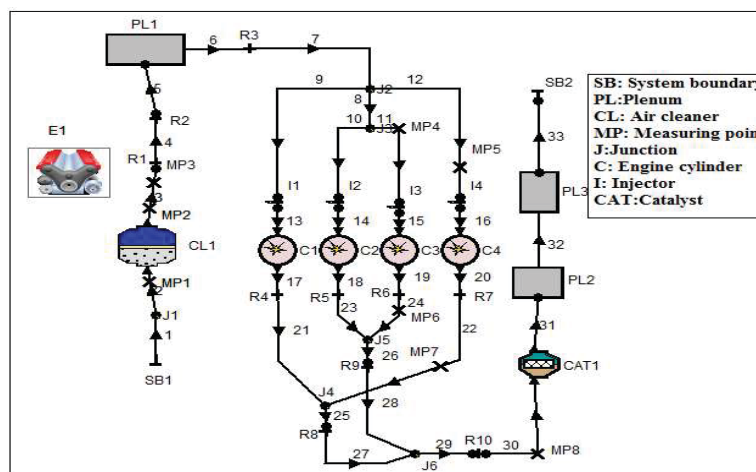
Figure 1. Schematic of the engine symbolic model by AVL Boost.

Table 1. Engine specification

Particulars	Specifications
Manufacturer	Hyundai
Engine Model	2.0 Liter, 16 Valves
Combustion system	GDI system
Number of cylinders	4 cylinders
Bore	81 mm
Stroke	97 mm
Compression ratio (CR)	17.5:1 (-)
Max power	118 kW at 5500 rpm
Max torque	142 Nm at 4500 rpm

This modelling is based on the first law of thermodynamics where the energy balance equation of the open system shown in following equation [16]:

$$\frac{d(m_c.u)}{d\theta} = -p\frac{dv}{d\theta} + \frac{dQ_F}{d\theta} - \sum\frac{dQ_w}{d\theta} - h_{BB}.\frac{dm_{BB}}{d\theta} + \sum\frac{dm_i}{d\theta}h_i - \sum\frac{dme}{d\theta}h - q_{ev}.f.\frac{dm_{ev}}{dt} \tag{1}$$

Where: $\frac{d(m_c.u)}{d\theta}$ change of internal energy in the cylinder, $-p\frac{dv}{d\theta}$: Piston work, $\frac{dQ_F}{d\theta}$: Fuel input heat, $\sum\frac{dQ_w}{d\theta}$: Wall heat losses, $h_{BB}.\frac{dm_{BB}}{d\theta}$: Enthalpy flow due to below-by, dm_e: Mass element flowing out cylinder, dm_i : Mass element flowing into cylinder , f : Fraction of evaporation heat from the cylinder charge, m_{ev}: Evaporation fuel.

2.1. *Instantaneous cylinder volume*
The instantaneous cylinder volume at any crank angle was calculated from below equations [16].

$$S = (r+l).\cos\psi - r.\cos(\psi+\alpha) - l.\sqrt{1-\left(\frac{r}{l}.\sin(\psi+\alpha)-\frac{e}{l}\right)^2} \tag{2}$$

$$\psi = \arcsin\left(\frac{e}{r+1}\right) \tag{3}$$

Where: *l*. Con road length, *S*. the distance from Piston to the top dead center, *a*. Crank angle relation to top dead center, *r*. Crank radius, *Ψ*. Crank angle between vertical crank position and piston top dead center, *e*. Piston pin offset.

2.2. Rate of heat release
In this work the combustion process is calculated by using the vibe two zone combustion (burned and unburned charge) as shown in the following equations [16]:

$$\frac{d(m_b.u_b)}{d\theta} = -p_c\frac{dV_b}{d\theta} + \frac{dQ_F}{d\theta} - \sum\frac{dQ_{wb}}{d\theta} + h_u\frac{dm_b}{d\theta} - h_{BB,b}\frac{dm_{BB,b}}{d\theta} \tag{4}$$

$$\frac{d(m_u.u_u)}{d\theta} = -p_c\frac{dV_u}{d\theta} + \frac{dQ_F}{d\theta} - \sum\frac{dQ_{wu}}{d\theta} + h_u\frac{dm_u}{d\theta} - h_{BB,u}\frac{dm_{BB,u}}{d\theta} \tag{5}$$

2.3. Heat transfer

In order to calculated the heat transfer coefficient produced from the chemical process of fuel between the combustion chamber and the cylinder wall, the Woschni model was selected as shown in below equation [16]:

$$\alpha w = 130 D^{-0.2}.p_c^{0.8}.T_c^{-0.53}.\left\{c_1.c_m.\left[1+2\left(\frac{V_{TDC}}{V}\right)^2 IMP^{-0.2}\right]\right\}^{0.8}$$

(6)

V: Actual cylinder volume, *V TDC.* Volume in the cylinder, *cu:* Circumferential velocity, *cm.* Mean piston speed, *IMEP.* Indicated mean effective pressure, C_l= 2.28 + 0.308 *Cu / Cm.

3. Result and discussions

A numerical model was developed by using AVL BOOST to study the effect of add a double gasket to the cylinder head on performance (effective power, torque and BSFC), combustion characteristic (cylinder pressure, cylinder temperature, peak fire pressure, peak fire temperature and rate of heat release) and emissions (NOx and soot) of GDI engine at different engine speeds (1000 to 3500 rpm, with increment 500 rpm) under full load engine.

3.1. Cylinder pressure

Figure 1 presents the variations of cylinder pressure related to the crank angle position, experimental and simulation results of the GDI engine at1000 rpm speed under constant load. As shown in this figure there is a good agreement between the simulation and experimental trace with a maximum relative deviation for peak fire pressure was 1.02%. Figure 2 shows the differences of the cylinder pressure trace related to the crankshaft position of the GDI engine with a single (original) and double gasket (C1 and C2, respectively) at different engine speeds under a constant engine load fueled gasoline fuel. From this figure, it was clear that the cylinder pressure value of the test engine with single and double gasket has a similar trend at all operating conditions. The cylinder pressure values of the GDI engine with a double gasket were lower when compared to that of a single gasket at all engine speeds. This reduction may be related to the increases in the combustion chamber size due to adding another gasket.
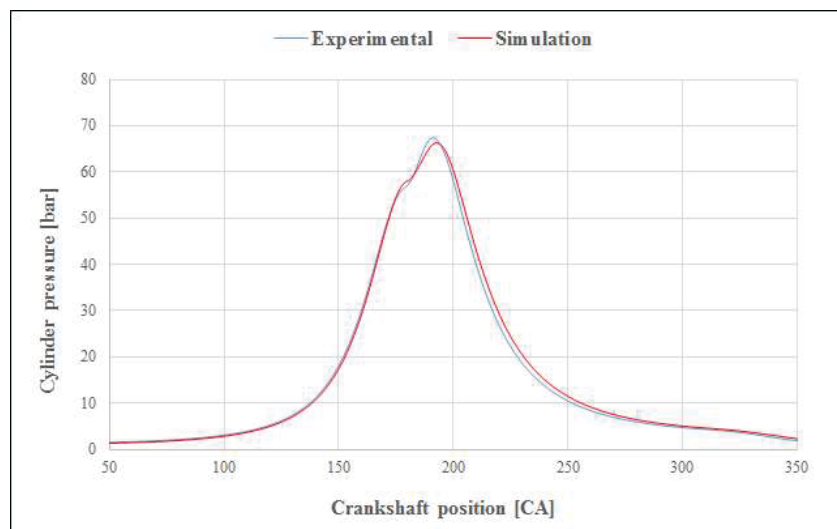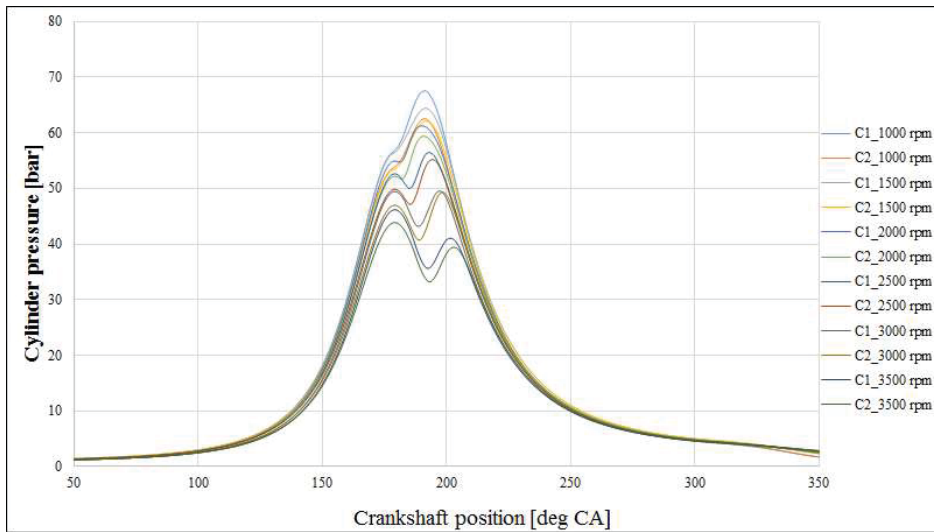

Figure 2. Comparison between experimental and simulation pressure for full load, 1000 rpm speed.

Figure 3. Variation of cylinder pressure of GDI engine with single and double gasket at different engine speeds.

3.2. Cylinder temperature

The variations of in-cylinder temperature related to the crankshaft position of the GDI engine with a single and double gasket at constant engine load with various engine speeds fueled gasoline showed in figure 3. It is clear from the figure that the gas temperature of the engine with double gasket traces was similar to that of the engine with a single gasket but with a lower value at operating conditions. This reduction in gas temperature could be related to the change in the combustion chamber dimensions which means more time need for the flame to reach the end of the combustion chamber and this affects the combustion process.
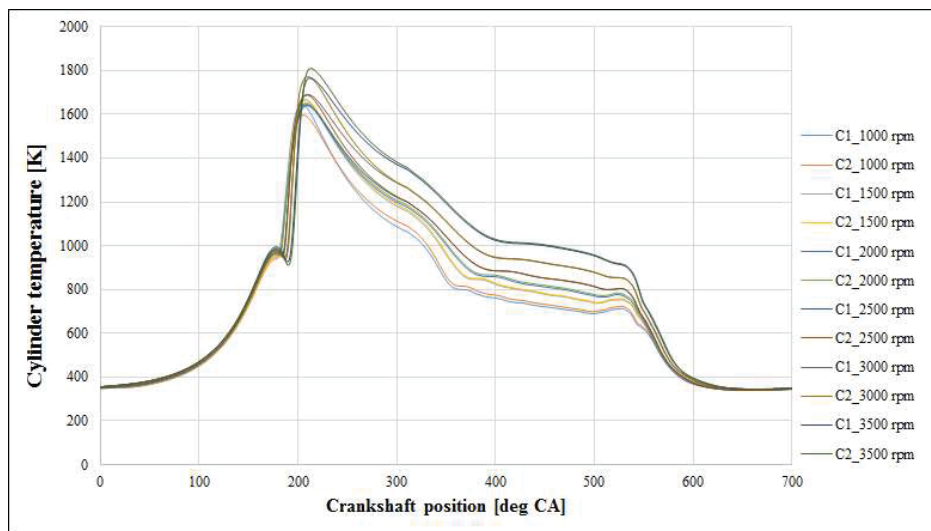
Figure 4. Variation of cylinder temperature of GDI engine with single and double gasket at different engine speeds.

3.3. Rate of heat release

The rate of heat release of the GDI engine with respect to the crankshaft position with a single and double gasket at a constant load and different engine speeds were numerically determined by the model are shown in figure 4. The engine with a double gasket showed delayed apparently in the rate of heat release than that of the engine with the single gasket at all operating conditions. This behavior could be related to the increases in the combustion chamber volume when adding a double gasket led to decreases in the cylinder pressure and temperature which resulting in the premixed stage of the combustion process.
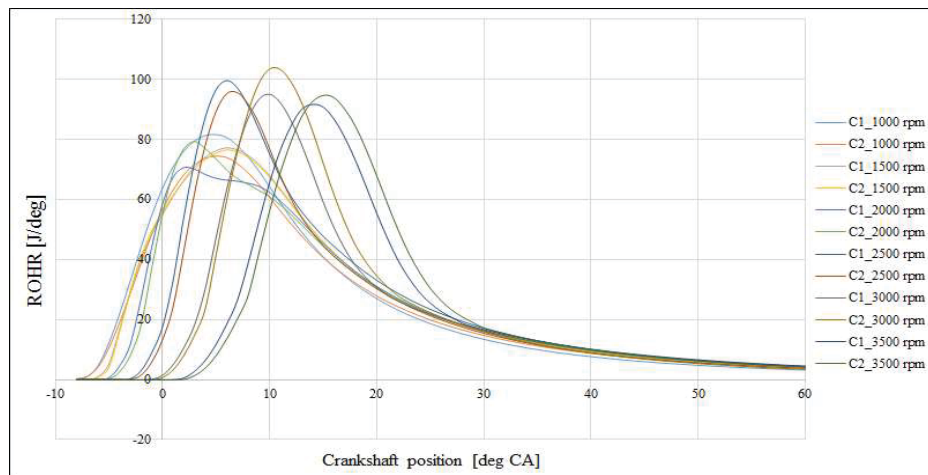

Figure 5. Variation of rate of heat release of GDI engine with single and double gasket at different engine speeds.

3.4. Peak fire pressure

The peak fire pressure created inside the combustion chamber of the GDI engine when used a single and double gasket at a selection engine speeds and load represents in figure 5. Simulation results reveal that the peak fire pressure of the test engine with a double gasket slightly lower than that of the engine with the single gasket at all operating conditions. The maximum deviation in peak fire pressure of the engine with single and double gasket reaches to 8% was registered at engine speed 1000 rpm.
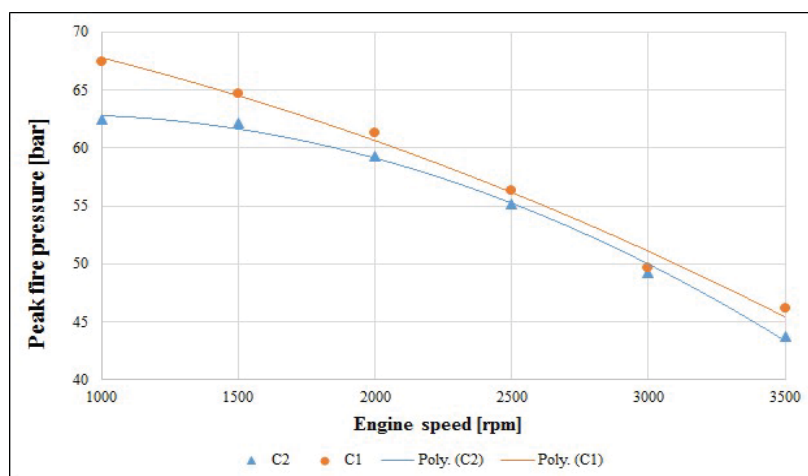

Figure 6. Variation of peak fire pressure of GDI engine with single and double gasket at different engine speeds.

3.5. Peak fire temperature

The peak fire temperature produces from fuel inside the combustion chamber has a direct influence on engine performance and emissions formation. Figure 6 shows the effect of adding a double gasket on the peak fire temperature of the GDI engine when operating on gasoline at a different engine speed. The peak fire temperature of the test engine with a double gasket is observed to be lower than that of the engine with a single gasket at all operating. This reduction because of the increases in the combustion chamber volume when adding another gasket which results in the combustion phases and duration coupled with the decreases in the flame distance. The maximum peak fire temperature of the engine with a double gasket was 1767.33 K and with single gasket was 1810.87 K at engine speed 3500 rpm.
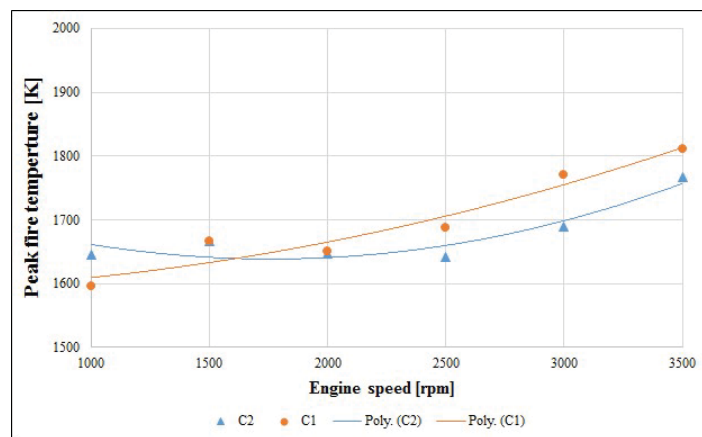

Figure 7. Variation of peak fire temperature of GDI engine with single and double gasket at different engine speeds.

3.6. Effective power

The effective power of the GDI engine fueled with gasoline fuel at different engine speeds when used a single and double gasket at constant load shown in figure 7. As illustrated in this figure, the effective power for both single and double gaskets increases when the engine speed increases. Overall selected operation conditions, the GDI engine with a double gasket produced lower effective power up to 5.67% when compared to that of the engine with a single gasket (original). This reduction related to the change in the combustion chamber volume because adding the second gasket and lead to decreases in the ratio of the swept volume to the total volume which resulting in the combustion process.
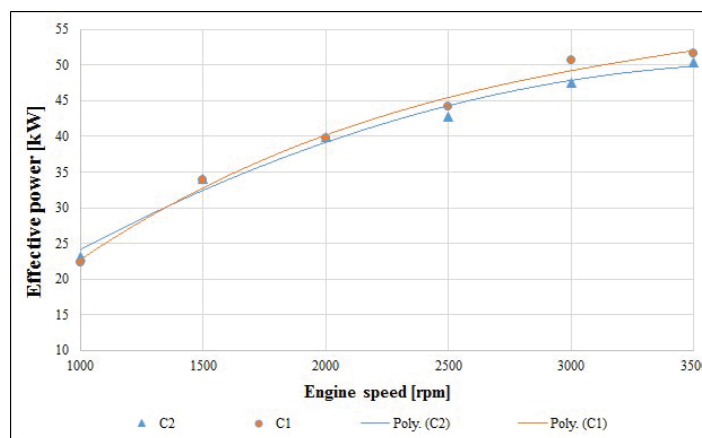

Figure 8. Variation of effective power of GDI engine with single and double gasket at different engine speeds.

3.7. Effective torque

Figure 8 shows the effective torque of the GDI engine fueled with gasoline fuel at a different engine speed for single and double gasket at full load engine. As shown in this figure, the effective torque produced by the test engine decreases when the engine speed increases. The maximum effective torque was identified by the engine with a single gasket was 220.75 Nm at 1000 rpm speed, while the engine with a double gasket was 213.48 Nm at the same engine speed. At all operating conditions, the engine with a double gasket produced lower effective torque than that of the engine with a single gasket.
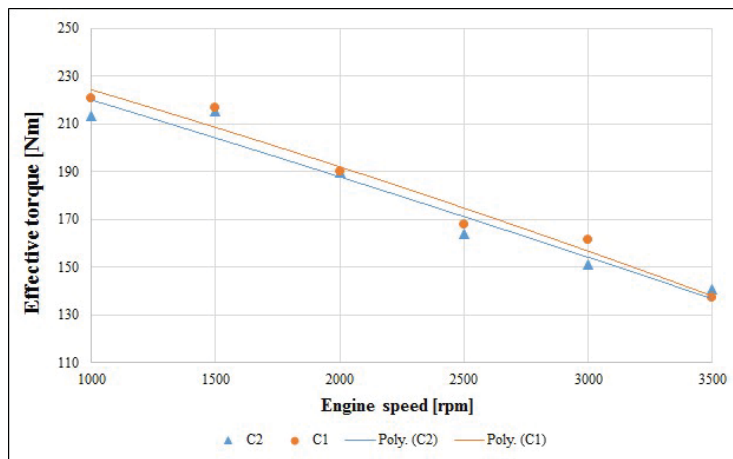

Figure 9. Variation of effective torque of GDI engine with single and double gasket at different engine speeds.

3.8. Brake specific fuel consumption (BSFC)

The BSFC is calculated from the amount of fuel consumed by the engine in the unit (kg/h) to produce effective power in the unit (kW). Figure 9 shows the variation of BSFC related to the engine speeds predicted by the simulation model. It can be observed that the BSFC engine was higher when used a double gasket in comparison to that of the engine with a single gasket. This behavior due to decreases in the cylinder temperature as a result of the change in the combustion phases when added to the double gasket which leads to incomplete fuel combustion. The maximum brake specific fuel consumption of the engine when added the second gasket register at engine speed 3500 rpm was 341.09 g/kW.hr, while the engine with the original gasket was 332.7 g/kWh.
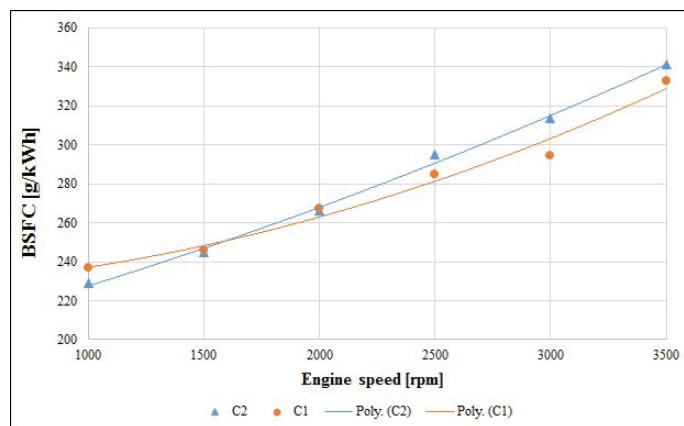

Figure 10. Variation of BSFC of GDI engine with single and double gasket at different engine speeds.

3.9. Oxide of nitrogen NOx

The production of oxide of nitrogen NOx emissions from the internal combustion engine is affected by many factors such as the cylinder temperature, the availability of the oxygen and the time residence. The variations of NOx with respect to the engine speeds of the engine with a single and double gasket shown in figure 10. As shown in this figure, the NOx emissions decrease when adding the second gasket at all engine speeds. The NOx emissions of the engine with a double gasket were lower than that of the engine with a single gasket at all operating conditions. This reduction could be related to the lowered in the cylinder temperature. The NOx emissions emitted by engine with double gasket was reached to 15.7% lowered than that of the engine with a single gasket at engine speed 3000 rpm.
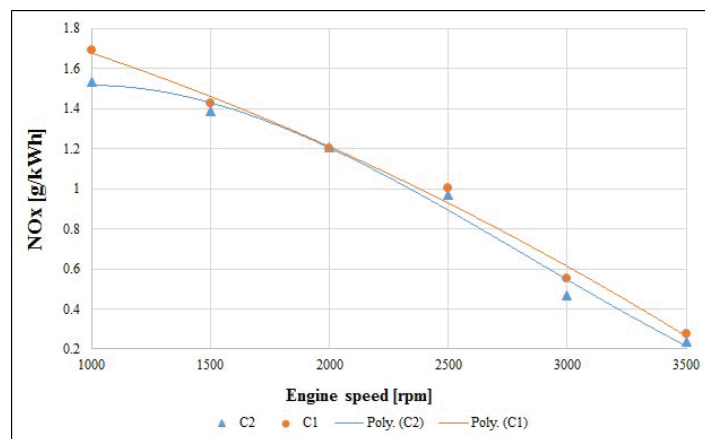

Figure 11. Variation of NOx of GDI engine with single and double gasket at different engine speeds.

3.10. Soot emission

The formation of the soot emission inside the combustion chamber was affected by the gas cylinder temperature. The variations of soot emission related to the engine speeds for a single and double gasket at different engine speeds are shown in figure 11. As shown in this figure, the engine with a double gasket emitted higher soot emission compared to that of the engine with a single gasket. This behaviour may be related to the reduction in the cylinder gas temperature when adding the second gasket. The max increases in soot emission of the engine with double gasket was 22.9% than that of engine with single gasket registered at speed 3000 rpm.
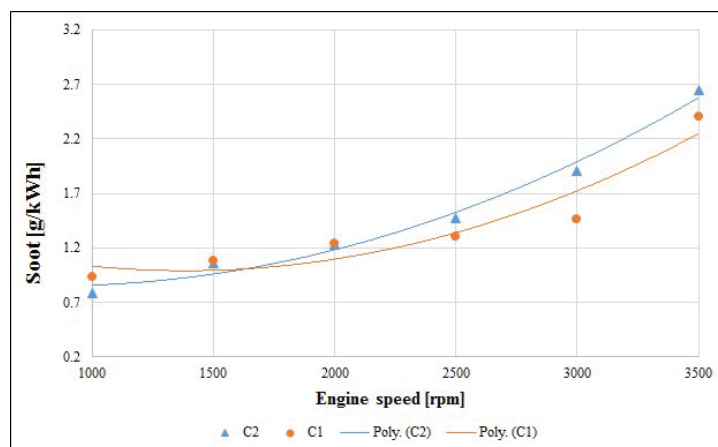

Figure 12. Variation of soot emission of GDI engine with single and double gasket at different engine speeds.

4. Conclusions

The effect of the double gasket on performance, combustion and emissions of the GDI engine using gasoline fuel was numerically developed. For this purpose, a model was developed by using the AVL BOOST program. The model was checked by comparing with experimental data related to the cylinder pressure. The study was carried out by using a four-cylinder, four-stroke direct-injection system engine. The results collected at engine speeds (1000 rpm to 3500 rpm, with increment 500 rpm) and a constant engine load. The main results can be concluded:

- The effective power and effective torque decreased up to 5% after the double gasket was replaced by a single gasket.
- The BSFC was slightly higher when adding the second gasket.
- There was improvement recorded in the NOx emissions when used a double gasket. which may perhaps be associated with the changes in combustion gas temperature.
- There was a minor deviation regarding the soot emission at adding a double gasket.
- The peak fire pressure and temperature of the engine with a double gasket were lower than that of the engine with a single gasket.

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