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COMPUTATIONAL STUDY OF THE EFFECT OF VARIABLE COMPRESSION RATIO ON THE PERFORMANCE OF AN INTERNAL COMBUSTION ENGINE

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Abstract. *Internal combustion engines are a subject which draws an extensive number of researches and studies, reaching incredible technological levels, nevertheless, the automotive industry still seeks for new technologies that could enhance the use of fuels' energy and engine performance. Variable compression ratio is one of the most promising in-cylinder technologies that has been studied in recent past. The present study is a computational investigation on how the behavior of different engine performance parameters such as break mean effective pressure, torque, volumetric efficiency and specific fuel consumption varies within a range of different compression ratios (8:1 to 16:1). A four cylinder, four stroke, naturally aspirated, engine model using gasoline as fuel was created in the Diesel RK software and several simulations, using four different engine working speeds, were carried out. Optimum points of compression ratio, at which the engine reached its best performance in terms of the monitored parameters were found, thus creating a map of the most advantageous compression ratios and parameters improved by them. Furthermore, the study highlighted the positive implications of the development of variable compression ratio engines, by comparing the engine performance achieved using the current fixed compression ratio to the performance achieved using the ideal compression ratios pointed out in the simulation results.*

Keywords: *Variable Compression Ratio, Engine Performance, Computational Study.*

1. INTRODUCTION

Researches on the development and improvement of internal combustion engines (ICE) normally gravitates around studies of alternative fuels that could minimize pollutant gases emissions and maximize engine efficiency. Several technological advances, including the introduction of biofuels such as ethanol, have been implemented in the recent past. In this context of search for alternative technologies, the idea of ICE with variable compression ratio (VCR) arises.

Roberts (2003) presented a theoretical examination of the relationship between compression ratio, break mean effective pressure and spark advance at light load and full load. The results showed the potential benefits of variable compression ratio on fuel economy and, moreover, identified the VCR as a key enabling technology to downsize engines. Yamin and Dado (2004) carried out computational simulations of a four stroke engine with variable stroke length, in another words an engine with variable compression ratio. A maximum increase of approximately 62% in the indicated power and a decrease of 6% in specific fuel consumption were obtained according to their results.

Thomas *et al* (2016) conducted an experimental investigation on the variation of parameters such as the thermal efficiency, exhaust gases temperature and emissions for three different compression ratios in a mono cylinder engine. The study results showed thermal efficiency improvement with the increase in compression ratio, explained by the boost in the work performed by combustion gases on the piston. Similarly, Srinivas *et al* (2012) performed an experimental study on a two strokes en engine, modified to work on four higher different compression ratios. According to their results, the increase in compression ratio caused a decrease in specific fuel consumption, as well as an improvement on thermal efficiency.

Studies on VCR first surfaced during the last decade, since then much has been discussed about its effects on engine performance, nevertheless the subject still lacks of studies for a better evaluation of the real advantages of this technique. In this sense, this study aims to analyze the improvement in performance that could be potentially achieved by enabling an ICE to change its compression ratio during operation. The analysis was performed through computational simulations of an ICE using the software DIESEL-RK, developed by Shovelful (2012).

2. MATERIALS AND METHODS

The engine specification used as model for the simulations is shown in Table 1.

Table 1 – Engine Specification

Engine Parameters	Value
Engine	GM (1982)
Fuel	Gasoline
Number of Cylinders	4
Ignition Order	1-3-4-2
Bore (mm)	86
Stroke (mm)	86
Displacement (cm³)	1998
Compression Ratio	8:1 – 16:1

Experimental data regarding the performance of this particular engine is found in Ferguson (1986), and later, in Silva (2004), thus, used as a mean of validation of the software simulation results in early stages of the study. Fig. 1 exhibits the break power developed by the engine, on different working speeds and compression ratio fixed at 12:1, according to the experimental values measured by Ferguson (1986) and by the present model simulation. The overall agreement in the behavior, as well as in the values achieved by both curves can be noted.

The 4000 rpm engine speed, Fig. 1, is used as an example to emphasize the proximity in break power values found by the simulation and the experimental data, Ferguson (1986) measured 62 kW, Silva (2004) in his thesis similarly measured 62 kW, the current work obtained 67 kW as result of the model simulation, satisfactory accordance, thus validating the use of the software.

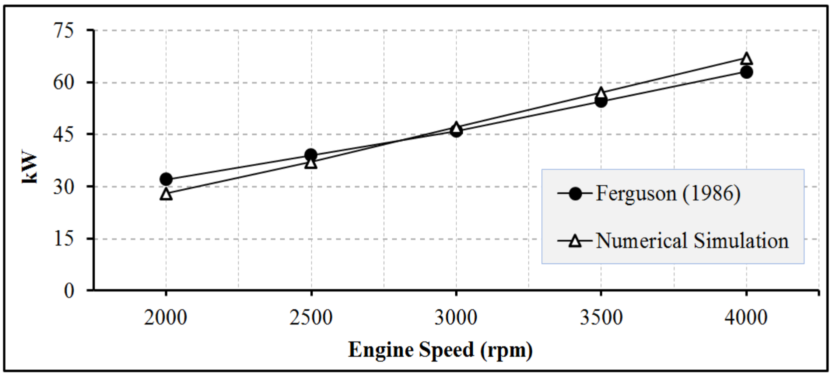

Figure 1: Comparative between experimental and simulated (present study) break power curves.

Simulations of the engine specified in Tab. 1, covered four different working speeds, 1500, 2000, 3000 and 4000 rpm, likewise Silva (2004) in his experimental tests. At each speed, the engine performance was evaluated for compression ratios between 8: 1 and 16: 1, this range was carefully chosen to comprehend the typical compression ratio values used in ICE fueled by gasoline (9:1), ethanol (12:1), in addition to the intermediate values adopted by dual fuel vehicles (flex).

Four parameters were monitored during the simulations, the mean effective pressure (MEP), torque, specific fuel consumption (SFC) and the volumetric efficiency.

3. RESULTS AND DISCUSSION

Simulation results are presented in the following order, firstly the variation of break mean effective pressure (MEP), torque, specific fuel consumption and lastly the volumetric efficiency.

The variations of break mean effective pressure (BMEP) at compression ratios varying from 8:1 to 16:1 are indicated in Fig. 2. In the lower working speeds (1500 and 2000 rpm), the BMEP peaks are situated at lower values of compression ratios, they are close to 9: 1. In overall, engine speed increments caused the peaks developed by the engine to move to higher compression ratios, the 4000 rpm curve for instance, reached its maximum BMEP value, 1000 kPa, at a compression ratio equal to 11,4 :1.

As seen in Fig. 2, it was noticed that the developed power peaks (with respect to the compression ratio) vary according to each engine working speed curve. There are different optimum working points of the compression ratio (peaks of the BMEP), which vary according to the engine rotation, hence justifying the concept of variable compression ratio engines.

Similar results were found by Silva (2004), the gradual magnitude growth in the BMEP curves at higher working speeds. Fig. 2 illustrates what is also presented in the literature, engines perform better in the high rotation regimes, while in the low regimes there will be a loss in performance as well as a trend towards increased fuel consumption.

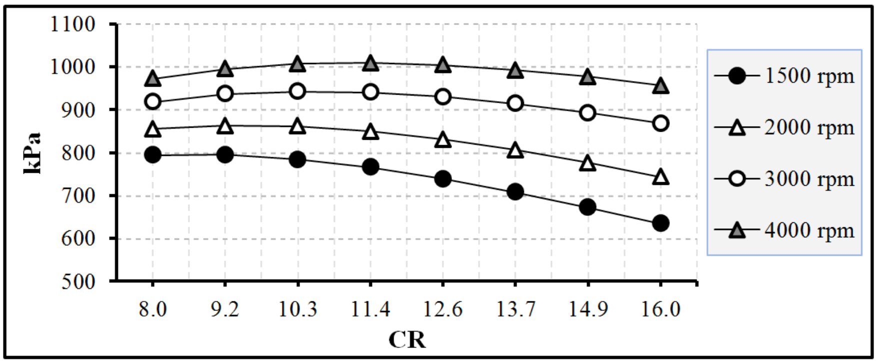

Figure 2: Break Mean Effective Pressure for different CRs and Engine Speed

Torque development in relation to the compression ratio and engine working speed is exhibited in Fig 3. The behavior is quite similar to the one seen for the BMEP, since there is a direct relationship between these two variables, note the increase in torque for higher rotations. At lower rotations, the highest torque values are developed at compression ratios between 8: 1 and 10: 1, and at higher working speeds (3000 and 4000 rpm), torque peaks occur at compression ratios between 10: 1 and 12: 1.

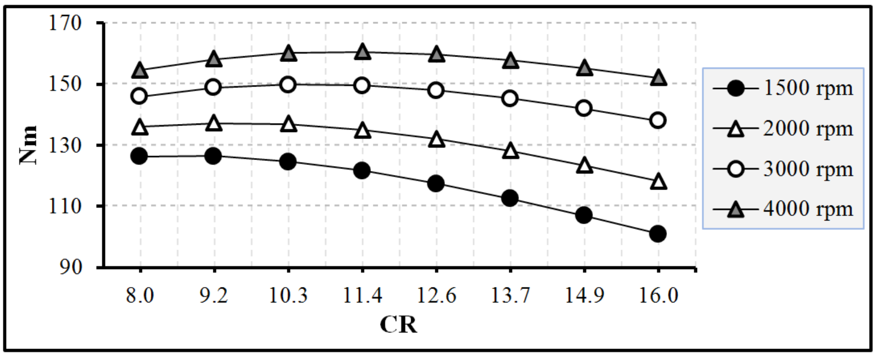

Figure 3: Break Torque for different CRs and engine speed

Torque values are in the same magnitude range as those found by Silva (2003), in his study the maximum torque measured was 152 Nm for the 2000 rpm rotation, at compression ratio of 12: 1 and using ethanol as fuel. The torque developed for the same rotation, compression ratio, fuelled by gasoline, according to the simulations is smaller, 134 Nm as it can be seen in Fig. 3. As expected, at higher compression ratio (12: 1), the combustion of ethanol was favored, since it has chemical properties which allow the compression ratio to increase, increasing temperature and pressure within the cylinder, without causing pre ignition.

Given the difference in performance between ethanol and gasoline by adopting the same engine working conditions for both fuels, as seen previously, a variable compression ratio mechanism would optimize the use of dual fuel engines, enabling the engine to use either fuels at the appropriate compression at all times.

Fig. 2 and Fig. 3 show how the break mean effective pressure and engine torque relate to the compression ratio, it is observed there are different optimal operating points for the compression ratio according to the engine speed. In general, higher pressure is generated in the cylinder as the compression ratio is incremented, thus increasing the work performed by the piston and also the break mean effective pressure. However, there is a maximum optimal break mean effective pressure and torque that can be achieved by increasing the compression ratio, from this point on, the increase in the compression ratio causes a decline in both parameters.

The drop in engine performance through excessive increase in compression ratio (after the critical value) was also reported in Balki & Sayin (2014) experiments, they explain that the decrease in torque and break mean effective pressure occur due to the exaggerated combustion chamber size decrease when excitedly high compression ratios are imposed, making the combustion slower and thermally inefficient. Moreover, greater losses occur due to the friction between the piston and the cylinder, caused by the increased length of the stroke.

Fuel consumption behavior regarding the variation of CR is shown in Fig. 4, it confirms the theory discussed in the literature, the increase in the working speed allows the combustion to improve thermodynamically, thus the engine consumes less fuel to generate power.

The increase in compression ratio favors a lower fuel consumption up to a certain CR limit value, 11.5:1 for the 3000 rpm and 4000 rpm curves, from this value on, the consumption is increased by increasing the compression ratio. The higher compression ratios may lead to spontaneous ignition within the cylinder, which turns the combustion thermodynamically inefficient, increasing specific fuel consumption as seen in Fig. 4.

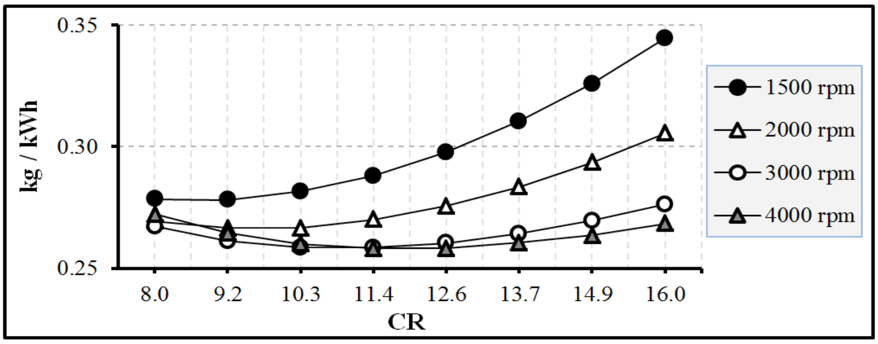

Figure 4: Specific Fuel Consumption for different CRs and engine speed

The variations of volumetric efficiency at different compression ratios are indicated in Fig. 5. In general, it could be observed that the volumetric efficiency increases with the increase of the engine working speed, while it decreases with the increase in compression ratio.

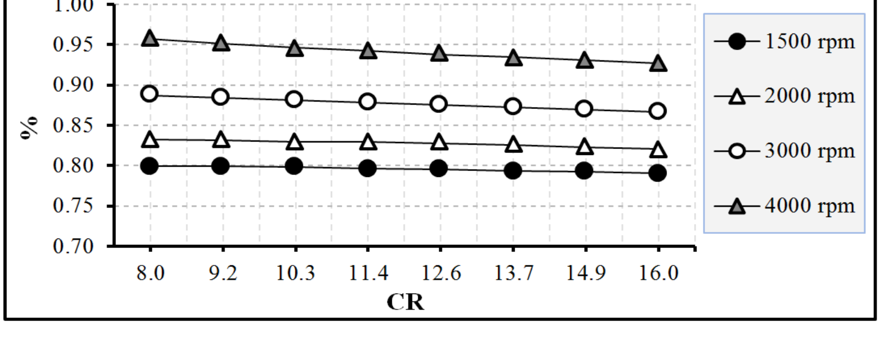

Figure 5. Volumetric Efficiency for different CRs and engine speed.

Low compression ratios presented the highest values in terms of the volumetric efficiency, the rotation of 4000 rpm for example, at the compression ratio of 8: 1 developed a volumetric efficiency of 0.955. For the same working speed, the volumetric efficiency was only 0.93 when the compression ratio was set at 16: 1. Lower pressure inside the cylinder (low compression ratio) increases the difference between the external pressure in the intake system and internal pressure within cylinder, facilitating air mass flow into the cylinder and therefore higher volumetric efficiencies.

In order to facilitate the understanding of the relationship between compression ratio and optimum values of torque, BMEP, volumetric efficiency and specific fuel consumption, data generated in the simulations were gathered and organized into a table with all most favorable points and their compression values, Tab. 2.

Tab. 2 should be interpreted as a map of the best compression ratios for this particular engine, it allows an overview of the possible advantages of variable compression ratio engines.

Table 2 – Best compression ratio for each of the parameters monitored

	Optimum Value / Correspondent CR			
Engine Speed (rpm)	*MEP (kPa)*	*Torque (Nm)*	*SFC (kg/kWh)*	*Volumetric Efficiency (-)*
1500	795 / 9.14	126.5 / 9.14	0.278 / 9.14	0,798 / 8
2000	863 / 9.15	137.3 / 9.15	0.267 / 10.3	0.832 / 8
3000	942 / 10.3	150 / 10.3	0.258 / 11.4	0.887 / 8
4000	101 /11.4	160.56 /11.4	0.256 / 11.4	0.955 / 8

Through evaluating optimum CRs for the working speed of 3000 rpm, Tab. 2, an interesting situation is observed, the optimal torque value of 150 Nm was obtained at the critical compression ratio of 10.3, while the lowest fuel consumption was 0.258 kg / kWh at the compression ratio of 11.4, it becomes clear that there are specific compression ratio values that prioritize engine power over fuel economy and vice versa, so a compression ratio control mechanism would allow the use of both characteristics, the economical mode and the most powerful mode, changing the compression ratio accordingly to the particular needs of each situation faced by the engine.

The 2000 rpm working speed also presented two critical compression ratios, 9.15, at which the highest torque was developed (137.3 Nm) and 10.3, at which the lowest specific fuel consumption was achieved. As for the 3000 rpm, there is clearly purpose for a variable compression mechanism control.

Otto cycle, gasoline internal combustion engines normally work at a compression ratio close to 9: 1, at this compression ratio for the 3000 rpm curve (Fig. 5), the specific fuel consumption is 0.262 kg / kWh, comparing this value to the optimum consumption for this rotation, which is 0.258 kg / kWh at the critical compression ratio 11.4: 1 (Tab 2), an economy of 1.53% in SFC would have been achieved be changing the CR from 9:1 to its optimum value. Likewise, a gain of 1.4 Nm in torque would be possible if the adopted compression ratio was 10.3: 1 instead of the standard compression ratio of 9: 1 which generates 148.6 Nm, the increase with this change would be close to 1%.

Moreover, the results displayed in Tab. 2 show that the highest values of the volumetric efficiency in each of the four engine rotations simulated happened at the same compression ratio, 8: 1, the efficiency dropped given any increment in the compression ratio. This behavior can be explained by the fact that the intake of the air / fuel mixture in the cylinder depends on the relation between the pressure of the intake system and the pressure within the cylinder itself, in order to the mixture be aspirated, the pressure within the cylinder must be smaller than the intake system. Lower CR translates to low pressures within the cylinder, therefore it facilitates the mixture intake, boosting the volumetric efficiency.

4. CONCLUSIONS

The effect of the compression ratio on the performance of an internal combustion engine was evaluated through numerical simulations using the Diesel-RK software. A four-stroke, four-cylinder, 1.98-liter, gasoline fueled GM (1982) engine was used as object of study and modeled in the software. The model was simulated in four different working speeds (1500 rpm, 2000 rpm, 3000 rpm and 4000 rpm) at the compression ratio range of 8: 1 to 16: 1. Initially, in order to validate the use of the software, simulation results were compared to experimental data available and good agreement was found.

By assessing four main engine performance parameters, break mean effective pressure, torque, specific fuel consumption and volumetric efficiency, at all four rotations and within the entire compression ratio range, the disadvantages of currently fixed compression ratio were better understood.

It was found that the optimal compression ratio for the engine varies even within a single working speed, on top of that it also depends on the performance parameter of interest. The study has shown that a variable compression ratio mechanism can enable gains in fuel economy, a reduction of 1.55 % in SFC was found by assuming the optimal compression ratio for the 3000 rpm working speed. Real gain in torque was also reported in the work when the optimum compression ratios were compared to the currently used fixed compression ratio in gasoline engines.

The work corroborates the knowledge expansion on the concept of variable compression ratio engines, it has shown the potential involved in the implementation of this technology in internal combustion engines. Based on the results of this study, it can be concluded that the performance parameters are indeed a function of compression ratio and therefore they can be enhanced by enabling variable compression ratio engines.

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6. RESPONSIBILITY NOTICE