Effects of Ethanol-Gasoline Blends, Compression Ratio and Cylinder Head Material on Engine

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***Abstract*– A Design of experiments methodology was carried out to investigate the effects of the compression ratio, cylinder head material, and fuel composition, on the engine speed, fuel consumption, warm-up time, and emissions of a carbureted single cylinder air-cooled spark ignited engine. The work presented here is aimed at finding out the sensitivity of engine responses, as well as the optimal combination between the abovementioned parameters. Engine performance was evaluated based on the changes in engine speed at idle conditions. Regarding the exhaust gas emissions, the concentrations of CO2, CO, and HC were recorded.**

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I. Introduction

Measures for reducing the reliance dependency on fossil-fuels for combustión engines include improving efficiency and substitution of gasoline with alternative fuels. Among these, ethanol is one of the most extensively used all over the world because of its high-octane, high combustion speed, and clean-burning.

The literature related to the performance assessment of SI automotive engine fed with ethanol-gasoline blends is abundant. However, most of the studies relate to automotive engines, while it is scarce the information related to the influence of the ethanol-gasoline composition on the performance of small non-road engines, those used in household and commercial applications, including lawn and garden equipment, utility vehicles, generators, and a variety of other construction, farm, and industrial equipment [3, 4]. Non-road gasoline engines differ from automotive engines in several technical specifications, and are very sensitive to the gasoline calibration. Because of these design differences, it is supposed that the effects of ethanol-gasoline blended fuel changes on performance and emission characteristics from non-road gasoline engines are quite different from the effects of ethanol-gasoline blended fuel changes on performance and emissions from automotive gasoline engines.

The sensitivity of the engine to the fuel composition depends also on the engine service life: the combustion chamber deposits (CCD) diminish the engine heat rejection (the conductivity of the engine walls decreases); the wearing process of the engine may lead to a reduction in the compression ratio. This is why in the present study it has been attempted a design of experiments methodology intended to evaluate the sensitivity of the engine warm-up time, performance, and emissions to the change in the fuel composition, the thermal wall properties, and the compression ratio. To simulate the reduced conductivity of the combustion chamber walls, for the cylinder head of the engine two materials, aluminum and cast iron, have been considered. To simulate the reduction of the compression ratio, a screwed cylinder has been placed in the spark plug location, augmenting the combustion chamber volume. The experiments are carried out based on the engine speed increase being calibrated for the baseline engine. The data collection is done during warm-ups and also at idle conditions.

The paper here presented is a report of the first steps made under a research in progress, and relates mainly to the performance of the engine at idle conditions. In the following parts of this document a brief description of the experimental set-up will be explained. Then it is given a brief explanation of the measuring methodology. In the third part of the paper results of the experiments are analyzed. Conclusions derived from the work close the paper.

II. EXPERIMENTAL SET UP

During idle and warm-up operating conditions, most of the SI engines run on rich mixtures, which cause incomplete combustion, and CO and unburned HC emissions increase [1-3]. Favourable factors for reducing these emissions are the increase of compression ratio, the reduction of heat losses, and the induction of oxygenated gasolines. Thus, the aim of this work has been the evaluation of cylinder head material (cast iron, a less conductive material as compared to aluminum), compression ratio, and fuel composition on engine warm-up, performance and emissions at idle conditions, by the realization of an experimental design of experiment (DOE) plan. Besides the fuel supply with two fuels, the requirements to be met by the installation needed to perform the study here presented, were threefold. In the first place the engine had to allow an easy randomly selected removal and assembly of the aluminum or cast iron cylinder heads. In the second place a simple design of the means to change the compression ratio of the engine had to be considered. In the third place, the installation had to incorporate the instrumentation to measure the engine speed, fuel consumption, temperatures, and emissions.

A. Test engine

The engine used to perform the experiment was a single-cylinder ROBIN EY 15D of 143 cm3 swept volume. It is actually a good representative of the "utility engines" group (EPA's classification for non hand held equipment). This is a

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typical small engine found in some yard machine applications and also in pump and compressor sets.

B. The cast iron cylinder head References

To simulate the reduction of heat transfer from the cylinder walls, a cylinder head made of cast iron was fabricated, preserving the integrity of the original design. The thermal conductivity of the cast iron is approximately three times lower than that of aluminum.

C. Change in the compression ratio

The solution proposed here to change the compression ratio is similar to those used in stratified charge engines. The insert is shaped in a form of the hollow cylinder. Such solution, with no moving parts, does not require major changes in cylinder head and consequently is more adaptable to the baseline engine. With the adapter, the original compression ratio 7,2 is reduced to 6,6 in the modified engine. The value from 7,2 to 6,6 is representative of a used worn out engine.

D. Test fuels

Ideally, an engine would be optimized for its fuel. In the case of the non-road engine, however, it is not easy to take full advantages of the properties of ethanol, simply because the engine has to compromise for operations on gasoline. The ethanol-gasoline mixtures that were used in this work were E10 and E20. The "E" refers to ethanol by volume in the blend, and the "10" refers to 10% ethanol, 90% gasoline. For the preparation of the mixtures, the automotive gasoline was used along with ethyl alcohol of 99,7 % purity [13]. Mixtures were prepared on a daily basis so that any possibility of content change due to evaporation or atmospheric humidity was minimized. The properties of the fuels used are shown in Table I.

TABLE I
PROPERTIES OF ETHANOL-GASOLINE BLENDS [13]

Quality parameter		Test method	Units	Base gasoline	Bio-gasoline E10	Bio-gasoline E20
Ethanol content		ASTM D5501	% vol.	7,7	12,3	22,3
Distilation range	10 % evapo	ASTM D86	ºC	51,8	52,3	53,4
	50 % evapo		ºC	87,9	69,1	70,8
	90 % evapo		ºC	161,4	159,3	154,9
	Final boiling point		ºC	217,3	206	201,2
Water content		ASTM E203	% vol.	0,061	0,087	0,136
Reid vapor pressure		ASTM D323	psi	8,8	8,7	8,4
Heating value		ASTM D3338	MJ/kg		45,86	44,8
Research octane number		ASTM D2699	RON	89	90,9	95

E. Measuring Equipment

A LEXUS balance, accurate to 0,5 g, and a 300 ml separating funnel were used to measure the fuel consumption; exhaust gases were sampled from the outlet and the CO, CO2, and HC emissions were measured with a QRO–401 gas analyzer; the engine speed was measured by means of a SKF serie TMRT contact tachometer; the engine temperatures were measured using FLUKE 54 II digital thermometer and two K-type thermocouples. Compression pressure of the engine was measured with a Milton compression meter. An illustration of the experimental setup is shown in Figure 1.

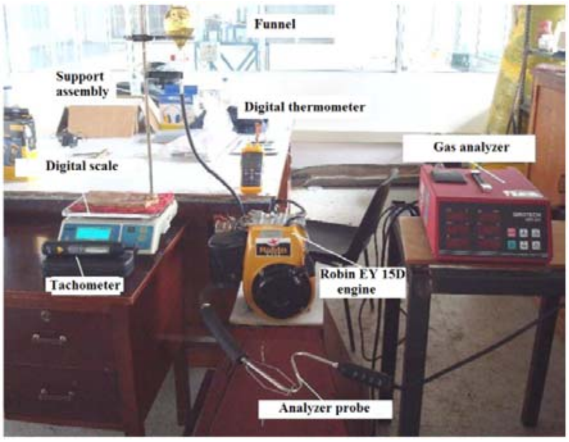

Fig. 1 Experimental test stand.

III. EXPERIMENTAL DESIGN

The installation described above was used to investigate the influence of the cylinder head material, fuel composition, and compression ratio on the warm-up time, engine performance, and emissions of the small gasoline engine. The performance of the engine is assessed based on the engine speed changes, initially calibrated for the baseline engine.

TABLE II
FACTORIAL DESIGN OF THE EXPERIMENT

Test Nº	Material	Compression ratio, ε	Ethanol-gasoline fuel blend
1	-1, Aluminum	1, 6,6	1, E10 (90/10)
2	-1, Aluminum	1, 6,6	-1, E20 (80/20)
3	1, Cast iron	-1, 7,2	1, E10 (90/10)
4	1, Cast iron	1, 6,6	1, E10 (90/10)
5	-1, Aluminum	-1, 7,2	-1, E20 (80/20)
6	1, Cast iron	-1, 7,2	-1, E20 (80/20)
7	1, Cast iron	1, 6,6	-1, E20 (80/20)
8	-1, Aluminum	-1, 7,2	1, E10 (90/10)

For the examination of the sensitivity of the global engine performance to the changes in engine walls conductivity (a change of the cylinder head material), compression ratio, and ethanol-gasoline mixture composition, a screening methodology was chosen. Selection of the values for the parameters of the factorial experimental design was based on a practical approach. Engine tests were performed without any engine modification (baseline) or engine settings, irrespective of the parameters change. The full factorial design was performed (8 tests) as described in Table II.

IV. RESULTS AND ANALYSIS

A summary of the processed results of 8 runs performed for each of the tests, are presented in Table III.

The statistical analysis of the results was performed, taking each response variable as a function of the varied factors. The analysis included analysis of variance table (ANOVA), Pareto chart, means plots, and response surfaces, but given the room available in this publication only a brief (not detailed) description of the results is presented, highliting the response of the warm-up time. For all pertinent tests significance was determined using a 0,05 p-value.

TABLE III
TEST RESULTS

Test Nº	Material	Compression ratio, ε	Fuel blend	Fuel consumption, ml/cycle	CO, %	CO_2, %	HC, ppm	RPM, min^{-1}
1	-1, Al	1, 6,6	1, E10	0,004976	0,36	5,15	2844	1651,5
2	-1, Al	1, 6,6	-1, E20	0,005243	0,19	5,10	3353,67	1576,7
3	1, CI	-1, 7,2	1, E10	0,004601	4,44	10,87	1698,67	2079,8
4	1, CI	1, 6,6	1, E10	0,004628	1,25	8,30	4603,50	1494,8
5	-1, Al	-1, 7,2	-1, E20	0,004225	0,62	12,20	1882,67	1920,5
6	1, CI	-1, 7,2	-1, E20	0,004096	1,79	11,57	2263,50	1931
7	1, CI	1, 6,6	-1, E20	0,005022	0,51	8,05	4714,67	1487,7
8	-1, Al	-1, 7,2	1, E10	0,004061	1,45	12,37	1564,17	2083

A. Fuel consumption analysis

The analysis of variance for fuel consumption is summarized in Table IV.

TABLE IV
FACTORIAL DESIGN OF THE EXPERIMENT

	Sum of Squares	DoF	Mean Squares	F-Ratio	P-Value
A:Material	3,10866e-9	1	3,10866e-9	0,04	0,8755
B: CR	1,04264e-6	1	1,04264e-6	13,15	0,1713
C:Flue blend	1,28721e-8	1	1,28721e-8	0,16	0,7561
AB	1,20222e-7	1	1,20222e-7	1,52	0,4342
AC	3,65446e-8	1	3,65446e-8	0,46	0,6203
BC	1,25776e-7	1	1,25776e-7	1,59	0,4272
Total Error	7,92617e-8	1	7,92617e-8		

The results show that there were no significant differences due to any of the studied factors, so neither was their interactions, though fuel consumption did experience a very slight but not statistically significant difference with compression ratio for the values comprised within the interval studied, and under idle engine operation. The relative importance of the controlled factors on fuel consumption was followed in the Pareto Chart, where compression ratio stood out. The maximum fuel consumption per cycle (0,00534314 ml/cycle) corresponds to the aluminum cylinder head, with the 6,66 value for compression ratio, and the E20 fuel blend. The minimum fuel consumption per cycle (0,00412516 ml/cycle) takes place with the aluminum cylinder head, a compression ratio of 7,2, and the E20 fuel blend. From the steepness of the surface response, it was concluded a solid trend in the influence of compression ratio on cycle fuel consumption, which decreases almost linearly with the compression ratio increase.

B. Fuel consumption analysis

Table V summarizes the analysis of variance for engine speed. There are no significant differences due to cylinder head material and fuel blend, though engine speed does experience a statistically significant difference with compression ratio. The Pareto chart supported this conclusion.

TABLE V
ANALYSIS OF VARIANCE FOR ENGINE SPEED

	Sum of Squares	DoF	Mean Squares	F-Ratio	P-Value
A:Material	7100,74	1	7100,74	19,48	0,1418
B: CR	406649,0	1	406649,0	1115,63	0,0191
C:Flue blend	19337,6	1	19337,6	53,05	0,0869
AB	8001,13	1	8001,13	21,95	0,1339
AC	827,024	1	827,024	2,27	0,3731
BC	6574,6	1	6574,6	18,04	0,1472
Total Error	364,5	1	364,5		

Means plots of engine speed are illustrated in Figure 2. While it is difficult to detect a significant difference between materials, the engine speed mean is greater with the 7,2 than with the 6,6 compression ratio value, the engine speed increase is around 22,5 %. The ethanol content change in the mixture has also a slight influence, though not as significant as the compression ratio has. It is higher in general the engine speed for the E10 fuel blend as compared to E20, what can partially be explained by its higher heating value.

The two separate response surfaces depicted in Figure 3 provide visual interpretation of factor effects on engine speed as a function of compression ratio and fuel composition for fixed cylinder head materials, aluminum and cast iron. From these graphics, it is clear that engine speed increases linearly with the compression ratio increase, and the reduction of ethanol in the fuel content. The higher engine speed, 2089,75 min-1, takes place for a combination of aluminum material, 7,2 compression ratio, and E10 fuel blend. The lower engine speed, 1480,92 min-1, occur with a combination of cast iron material, 6,6 compression ratio, and E20 fuel blend.

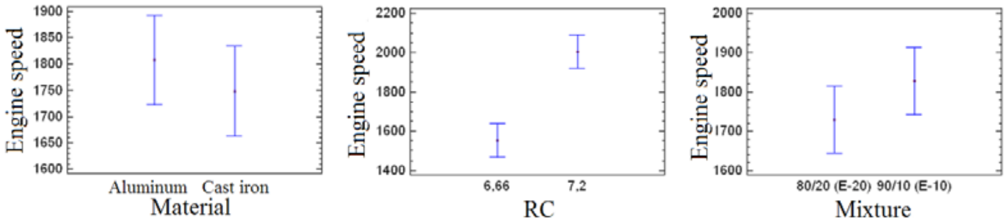

Fig. 2 Plots of engine speed means for the experimental factors studied.

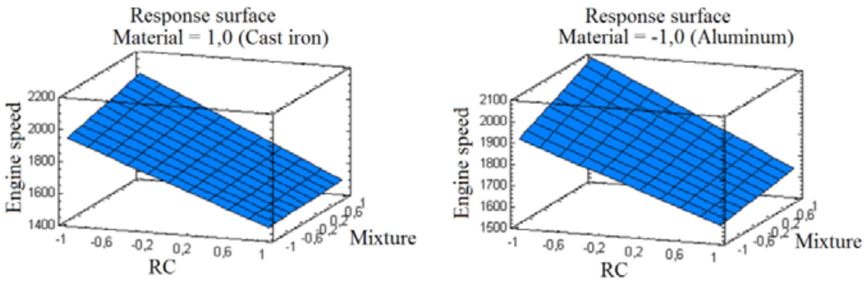

Fig. 3 Engine speed response surfaces for the experimental factors studied.

C. *Carbon monoxide analysis*

It follows from the analysis of variance, shown in Table VI and from the Pareto chart obtained, that the contributions of all the three factors studied are of the same order. Also, the influence of the interactions on the studied response is comparable to that of the main factors. This makes it difficult to isolate the influence of each of the factors involved. No conclusion can be made from the data collected as to a noticeable difference between the CO emissions responses to the changes performed in the controlled values of the experiment, except that their relative importance is comparable, with a very slight advantage in favor of the the compression ratio influence.

TABLE VI
ANALYSIS OF VARIANCE FOR CO EMISSIONS

	Sum of Squares	DoF	Mean Squares	F-Ratio	P-Value
A:Material	3,60461	1	3,60461	18,46	0,1456
B: CR	4,48501	1	4,48501	22,96	0,1310
C:Flue blend	2,40901	1	2,40901	12,33	0,1766
AB	1,08781	1	1,08781	5,57	0,2552
AC	0,714013	1	0,714013	3,66	0,3068
BC	0,825612	1	0,825612	4,23	0,2882
Total Error	0,195313	1	0,195313		

Response surfaces of the CO emissions as functions of the compression ratio and fuel blends at fixed cylinder head material showed a linear dependency between CO emissions levels and ethanol content in the fuel blend. In general, from the response surfaces, it can be concluded that with the cast iron cylinder head the CO emissions levels are higher than with the aluminum one. This could be attributed to the reduction of the cylinder head heat transfer, that generates a reduction in the volumetric efficiency, and consequently in the air content of the mixture.

D. *Carbon monoxide analysis*

From the values in the analysis of variance, Table VII, and Pareto chart, it can be pointed out the major effect the compression ratio has on the CO2 emissions, followed by the cylinder head material, and the interaction between these two factors. The means plots, allowed to conclude the higher mean CO2 emissions level produced with the higher compression ratio (a near 32 % increase in the emissions of CO2, by shifting the compression ratio from 6,6 to 7,2).

TABLE VII
ANALYSIS OF VARIANCE FOR CO2 EMISSIONS

	Sum of Squares	DoF	Mean Squares	F-Ratio	P-Value
A:Material	1,97011	1	1,97011	13,77	0,1676
B: CR	52,071	1	52,071	363,85	0,0333
C:Flue blend	6,6125e-3	1	6,6125e-3	0,05	0,8652
AB	8,46661	1	8,46661	59,16	0,0823
AC	5,61125e-2	1	5,61125e-2	0,39	0,6439
BC	8,61125e-2	1	8,61125e-2	0,60	0,5800
Total Error	0,143112	1	0,143112		

The increased emissions of CO2 are due to a better combustion. E10 and E20 fuel blends are nearly identical in terms of CO2 emissions means under the idle operating conditions studied, and without making changes to engine calibration settings. At these conditions, fuel properties such as the laminar flame speed and heat of vaporization can counteract the energy content in a fuel, as indicated by the heating value, to reduce the CO2 emissions.

The CO2 emissions means responses described the predominant linear influence of the compression ratio on the CO2 emissions, with a steeper slope for the aluminum material, meaning the sensitivity of the emissions to the changes in the thermal properties of the combustion chamber materials. Likewise for CO, the lower emission levels of CO2 take place for the aluminum cylinder head.

E. *Hydrocarbon emissions analysis*

The analysis of variance for hydrocarbons is shown in Table 8. Significant differences in the output variable are observed for the compression ratio factor, followed in sequence by the cylinder head material and the interaction of these two factors.

TABLE VIII
ANALYSIS OF VARIANCE OF HYDROCARBON EMISSIONS

	Sum of Squares	DoF	Mean Squares	F-Ratio	P-Value
A:Material	1,6524e6	1	1,6524e6	31,79	0,1117
B: CR	8,21509e6	1	8,21509e6	158,06	0,0505
C:Flue blend	2,82816e5	1	2,82816e5	5,44	0,2578
AB	8,48364e5	1	8,48364e5	16,32	0,1545
AC	2,89446e3	1	2,89446e3	0,06	0,8525
BC	8,61263e3	1	8,61263e3	0,17	0,7539
Total Error	5,19757e4	1	5,19757e4		

Pareto chart confirmed the strong influence of the compression ratio on HC emissions. Unlike the Pareto chart trend for CO2 emissions, the fuel composition exerts some influence on the unburned HC emissions levels. Increasing the ethanol content in the fuel, HC emissions decrease considerably at idle conditions.

Unlike the effects on CO and CO2 emissions, the increase of the compression ratio traduces into a reduction of the HC emissions. The HC mean is greater for the 6,6 than for the 7,2 compression ratio value, which is explained by the combustion process improvement, the reduction of crevice area and volume of the combustion chamber. With the aluminum cylinder head the mean amount of HC is lower than with the cast iron one. HC mean is slightly higher for the E20 fuel blend. It is difficult to draw a conclusion from the compression ratio and cylinder head material interaction, though some explanation may lay on the particularities of combustion and cleaning-up of the additional volume created to reduce the compression ratio, where the spark ignition is inserted.

HC emissions response surfaces as functions of the compression ratio and fuel blends at fixed cylinder head material showed steeper slopes for the cast iron cylinder head as compared to those of the aluminum ones.

F. *Warm-up analysis*

The variation of the engine temperature during the warm-up period, after the engine start, for all the tests carried during the experiment, is ploted in Figure 4. The warm-up period, defined here as the time required to reach the target temperature of 75 ºC, is displayed in the Table IX.

It is important to point out the elevated the cylinder head temperatures reached in the tests corresponding to the cast iron cylinder head in combination with the higher value of the compression ratio.

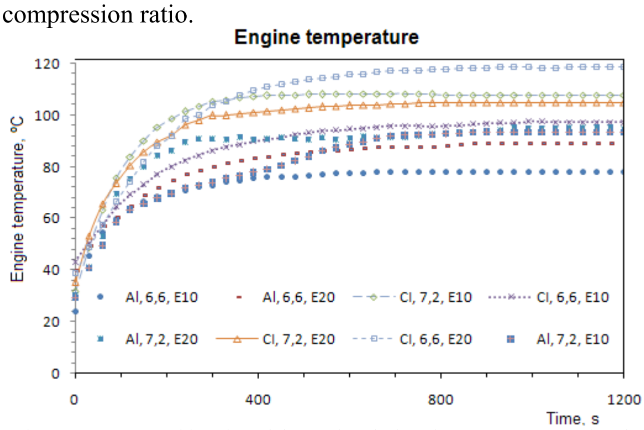

Fig. 4 Temperature histories of the engine during the warm-up operation for all the combinations of the experiment.

TABLE IX
SUMMARY OF THE TIME REQUIRED TO REACH THE ENGINE TARGET TEMPERATURE FOR ALL THE COMBINATIONS OF THE TEST PERFORMED DURING THE EXPERIMENT

Test number	Time, $t_{75°C}$, min	Test number	Time, $t_{75°C}$, min
1 (Al, 6,6, E10)	6	5 (Al, 7,2, E20)	1,9
2 (Al, 6,6, E20)	3,65	6 (CI, 7,2, E20)	2,1
3 (CI, 7,2, E10)	1,5	7 (CI, 6,6, E20)	1,7
4 (CI, 6,6, E10)	2,85	8 (Al, 7,2, E10)	5,4

As was expected, the steady state temperature is lower for the tests with aluminum cylinder head, because of its higher thermal conductivity (K≈ 170 W/m•K) as compared to that of cast iron (K ≈ 80,2 W/m•K).

The analysis of variance for engine warm-up time is shown in Table 10. Though no significant differences in the warm-up time are observed for the varied factors, it can be seen that the most influencing factor is the cylinder head material, followed by the fuel blend. The Pareto chart obtained confirmed the relative importance of the cylinder head material.

TABLE X
ANALYSIS OF VARIANCE OF ENGINE WARM-UP TIME

	Sum of Squares	D. of F.	Mean Squares	F-Ratio	P-Value
A:Material	1,36125	1	1,36125	1,29	0,4590
B: CR	5,12	1	5,12	4,87	0,2708
C:Flue blend	9,68	1	9,68	9,21	0,2027
AB	0,045	1	0,045	0,04	0,8701
AC	0,0245	1	0,0245	0,23	0,7137
BC	3,51125	1	3,51125	3,34	0,3187
Total Error	1,05125	1	1,05125		

The more sluggish (6,3625 min) to warm-up was the combination corresponding to the aluminum cylinder head, 6,6 compression ratio value, and E10 fuel blend. The engine warmed faster, 1,7375 min, with the cast iron cylinder head, 7,2 compression ratio value, and E20 fuel blend.

V. CONCLUSIONS

This research focused on a serial production small single cylinder gasoline engine for non-road applications, modified for running with two cylinder heads of different materials, one insert to modify the compression ratio, and two different ethanol-gasoline blends. The engine warm-up time, fuel consumption, change in engine speed, and emissions have been tested and compared. The test measured engine warm-up performance via cylinder head temperauture measurements, and quantified the engine performance in terms of engine speed increase at idle.

Based on the analysis of the response surface plots of the experiment, optimal sets of conditions for the engine studied under idle operating conditions have been summarized and displayed in Table XI.

TABLE XI
OPTIMIZATION OF THE RESPONSE VARIABLES

Response variable	Material		Comp. ratio	Fuel blend	Value
Fuel consumption per cycle, ml/cycle	Minimum	Aluminum	7,2	E20	0,0041
Engine speed, min^{-1}	Maximum	Aluminum	7,2	E10	2089,7
CO, %	Minimum	Aluminum	6,6	E10	0,2037
CO_2, %	Maximum	Aluminum	7,2	E20	12,333
HC, ppm	Minimum	Aluminum	7,2	E10	1483,5

Except for the CO emissions, the aluminum material and the higher compression ratio favor the engine performance and emissions levels. Not so conclusive is the influence of the fuel blend.

The results showed that the compression ratio plays the larger role for engine performance. At the same operating conditions, the engine speed for the cast iron cylinder head was higher compared to the aluminum cylinder head. The engine warm-up duration was larger for aluminum cylinder head, due to larger heat losses. The conclusions drawn from the results can only be applied to the factor level considered in the analysis, and cannot be extend to other similar treatments that were not explicitly considered.

In general, the study here presented found no statistically significant difference in overall performance between E-10 and E-20, which confirms the similarities of ethanol-gasoline blends with less than twenty percent ethanol at idle operating conditions.

A further study should focus on the influences of the fuel blend, compression ratio and engine material application under load conditions (observing the combustion chamber phenomena) on the engine power output; fuel consumption and engine exhaust emissions.

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