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Review Article

Effect of Injection Parameters and Emissioncharacteristics in a Common-Rail Direct Injection Diesel Engine in Height Conditions: A Review.

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Abstract

The common-rail direct fuel injection (CRDI), it is currently employed in diesel engines. The objective of this study is analyzing the combined effects of injection pressure and emission of a diesel engine with CRDI fueled with biodiesel in height conditions, for which an exploratory-explanatory investigation is carried out about the main works carried out in relation to this topic, applying the PRISMA methodology. A comparative analysis of emissions between diesel and biodiesel and the effect that height has on emissions is carried out It is concluded that pollutants such as particulate material, carbon monoxide and hydrocarbons are reduced three times less with the use of biodiesel, nevertheless, the value for nitrogen oxide tends to increase drastically up to 5 times more with the use of biodiesel, whereby biodiesel is a fuel alternative to reduce emissions without sacrificing significantly power factors and engines performance. In relation to the design, it is determined that the number of holes, the number of flat springs and the injection pressure are the three factors that have the most influence on the performance of the engine.

Keywords: emissions, diesel, performance, CRDi engine, altitude.

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1. Introduction

Diesel remains one of the most used fossil fuels in the industry, further, technological advances have allowed this fuel to occupy an important place as fuel for the automotive sector [1]. Biodiesel is one of the main prospective alternative fuels that can reduce the consumption of fossil fuels and exhaust emissions [2]. Currently a massive search for the use of vegetable oil in diesel engines is generated, followed by the use of biodiesel with technically improved characteristics [3-4]. In conjunction with technological progress, biofuels have attracted attention especially in the last decade [5]. Justly since 2009, it has been incorporated in Europe a legislation so that in 2020 at least 10% of the energy consumed in all transport it is going renewable. Currently, biodiesel is the most commonly used biofuel in Europe [6-7].

In order to comply with the proposed emission directives and consumer expectations of fuel savings, paradigm changes have been demanded in the diesel engine technology [8-9]. Among the various contingent technological advances, common-rail direct fuel injection (CRDI) allow that engine performance to rise and emissions to decrease. It be analyzes the different injection pressures that give better or worse results at the level of performance and emissions of this type of engine [10]. Similarly, the internal configuration of the injector directly influences the aforementioned engine parameters [11].

Additionally, the height, according to Kan [12], has a significant effect on combustion for heavy duty diesel engines. Thus, there are evaluated effects such as performance, fuel consumption and pollution to determine the degree of the altitude affectation even with the inclusion of biodiesel [13]. Few studies have investigated the effect of biodiesel on the performance and emissions of diesel engines at higher altitudes [14]. In efforts to achieve the reduction of engine emissions and fuel consumption while maintaining other engine performance at an acceptable level, fuel injection parameters play an important role [15]. The most important injection parameters are the injection time, the duration of the injection and the injection pressure. In this study of the literature review, the aim is to analyze the combined effects of fuel injection pressure and emission of a diesel engine with CRDI fueled with biodiesel in height condition.

2. Methodology

A systematic mapping of the literature was made [16], defining themes that influence each other such as: 1) characterization of the air-fuel mixture, 2) variation of the injection pressure, 3) different injection strategies to reduce polluting emissions, 4) results of the emissions in conditions of great heights. The purpose is to analyze the combined effects of fuel injection pressure and emission of a diesel engine with CRDI fueled with biodiesel in height condition. To guide the systematic mapping [17], the following research questions were defined: 1) What is the type of injector due to its characteristics (shape, type, control) presents better performance and less pollution?; 2) What is the effect of changing the geometry of the injector, its

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position in the chamber or the type of diesel on the injection pressure and the polluting emissions?; 3) Does biodiesel or other derived fuels actually provide the same characteristics as diesel and generate less pollution?; 4) How does diesel and biodiesel influence the height with respect to polluting gases?

The search of the studies and articles was carried out in the following bibliographic data bases: Science Direct, Applied Sciences, KSAE, Lectito, ASME JEGTP, Research Gate, Latindex, IJSR, American Chemical Science, SAGE. In each of them expressions or search keywords were applied. Among the main search keywords or expressions are: CRDI, diesel, *injection pressure*, *emissions, altitude* and biodiesel. As a complement to certain databases, we have added search parameters such as: diesel performance, injector, common rail and diesel engine to obtain somewhat more specific results in this regard, for which the PRISMA methodology was applied. In Table 1, the search structure is detailed [18].

Table 1. Search structure according to keywords and databases

Keywords	Database	Found	Selected	Per-cent
CRDI, Diesel, Injection Pressure	Science Direct	141	16	31%
Altitude, Diesel engine, Common Rail	Science Direct	96	6	12%
CRDI, Diesel, Emissions, Biodiesel, Common Rail	Science Direct	89	11	22%
CRDI, Injection Pressure, Emissions	Applied Sciences	3	2	4%
Diesel Injection, CRDI, Biodiesel	KSAE	24	2	4%
CRDI, Emissions	Lectito	2	1	2%
Diesel Pressure Injector	ASME JEGTP	316	1	2%
Diesel, Emissions, CRDI, Injection Pressure	Research Gate	100	6	12%
Diesel, Injection, CRDI	Latindex	7	2	4%
Diesel, CRDI, Emissions, Injector	IJSR	18	1	2%
Diesel, Biodiesel, Emissions	American Chemical Society	319	2	4%
Biodiesel, diesel performance	SAGE	55	1	2%
	Total	**933**	**51**	**100%**

This involved carrying out the search in 10 databases, obtaining a total of 933 documents found with the aforementioned search parameters. The documents that met the following inclusion criteria were selected: journal articles, scientific articles, international conference documents, without restriction of the publication date, but preferably selecting documents not smaller than 2008, unless the title and document provide significantly to work.

1 **Planning stage**

- Set keywords or search terms to use.
- Review literature and existing documents on CRDI diesel systems.

2.1 **Search stage: criteria inclusion**

- Selection of terms and keywords: diesel, biodiesel, CRDI, injection height and pressure.
- Dates of publications preferably between 2008-2018.
- Articles, documents or scientific journals that comply with a technical criterion, exhibit tests and results with numerical data.

2.2 **Search stage: exclusion criteria**

- Documents that, despite including keywords, these do not correspond to the search topic.
- Documents that are informative and non-technical.
- Non-academic documents or journals as opinion articles.

3 **Search results**

- Database used: 10
- Documents found: 933
- Selected documents: 51

Fig. 1. Summary literary review for article.

At the level of exclusion criteria, documents were separated that, despite including the keywords, the title and the subject of the document was not a technical analysis that involves technical evidence and results [19]. At the same time, documents that use tests on engines or cylinders that are not injection with common rail were also discarded. As an illustration, a summary is presented in figure 1.

3. Discussion

After reviewing the 51 selected publications, 117 influential contextual attributes were identified in the selection of eduction techniques. These attributes were classified according to the contextual factor to which they belong. Five factors were established: Eductor (who performs the eduction), Informant (who has the relevant information), Domain of the Problem (area of knowledge where the problem is lodged), Domain of the Solution (discipline and technologies that are necessary to generate a solution) and Process of Eduction (activities and environment in which the process is carried out).

3.1 Characteristics of injection in engines with CRDI

In diesel engines a robust compression ignition combustion depends largely on three factors, these are: the cylinder loading temperature, the composition and the cylinder pressure [10, 20]. As the cylinder pressure is a crucial factor, the variation of this pressure is analyzed. This depends in large part on the type of injector and the internal components [48]. According to Han, Kim, and Lee [21] in an injector, the high injection pressure depends on the number of flat springs. Without the presence of flat springs in the injector, the DPI cannot inject more than 1800 bar due to loss of elasticity, which leads to a less homogeneous spray inside the chamber. Therefore, the elasticity and pressure depend largely on the flat springs.

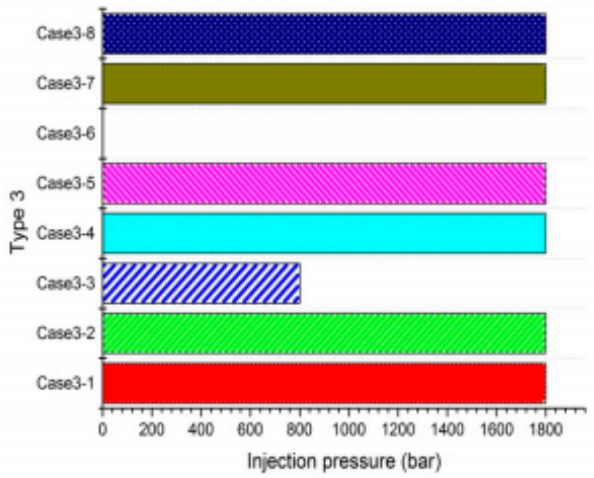

Fig. 2. Comparison of the maximum injection pressures of Type 3 DPIs [21].

In addition, to obtain better results regarding injection speed, the fundamental factor to consider is the plate of the DPI spring and the pressure plate of the needle since they are controlled only by mechanical systems or by hydraulic pressure [21]. As shown in figure 2, in short, the variation of springs and pressure plates inside the injector directly influences the injection pressure and the scope of injection or penetration inside the chamber. It can be said that the increase of these springs increases the pressure and penetration allowing a homogeneous spray inside the chamber. This applied to piezo-electric injectors where using at least one more pressure spring allows up to 100 bar compared to the conventional injector that injects up to 1 200 bar in the test conducted by Han, Kim & Lee [21].

In terms of efficiency, in a test carried out on a single cylinder of a CRDI diesel engine, it is found that its maximum injection pressure is 700 bar. The highest thermal efficiency results in 400 bar of pressure and it decreases while higher it been the pressures [22]. So Shahir [23] argues that in CRDI systems increasing the injection pressure above 700 bar reduces the number of fuel particle concentrations at full load of the engine, thus improving spraying. Likewise, at high pressures, and with the putting forward of the injection time, the same effect is obtained since the advance provides more time to mix the fuel drops with the surrounding air before starting the combustion.

According to Mane [24], when performing experiments varying the injection pressure, it was found that the performance was not greatly affected, since the load and pressure increase and the thermal efficiency increases while the specific fuel consumption decreases [50],. Regarding the performance, from the analysis of performance, it is found that at an injection pressure of 600 bar we obtain the optimal thermal efficiency (BTE) and the specific fuel consumption (SFC). This concludes that, with an injection pressure of 600 bar, both the performance parameters and the emission parameters are at an optimum value.

In the article by Chen [25], the spray and atomization of diesel and its alternatives are just analyzed by injection with a single-hole injector using a common rail system. The results show that the drops of the peripheral aerosol have a larger diameter than the drops in the center due to a greater pressure in the periphery. At the level of penetration, if working at high pressures, the drops are distributed more evenly and have less variation in their diameters [51]. For this reason, the higher pressures guarantee a better spray in the injection and greater penetration.

The injector is definitely an element directly related to engine emissions. This is how the precise control of the injector is one of the most important parts of the control of a CRDI engine [26]. The control of the actuator of the injector allows to obtain the best configuration depending on the duration of the injection and the pressure of the injected fuel. Hence the importance of the new injectors being piezo-electric. Between the characteristics of the importance of these injectors is the opening and closing much faster, precise control of intervals of injection that allow feedback with information to the computer of the vehicle. After setting the injection pressure and the injection quantity, the piezo injectors allow to reduce fuel consumption due to the fineness of the injected fuel spray [27].

In the study conducted by Payri [28] using a diesel injector solenoid with 2200 bar and 8 holes, the influence of the ambient temperature, the injection pressure and the density of the environment for penetration at high pressures is demonstrated. Temperature parameters of 150 bar and a temperature of 1000 K are established. Definitely the injection pressure variable directly affects the vapor penetration, but not so much in the liquid state. By maintaining the temperature parameters in the experiment, there is a small decrease in vapor penetration. It is estimated that this is due to the reduction in the size of the drops injected when heated [28]. Additionally, according to Som et al. [29] it is the cavitation and turbulence within the diesel injector that play a critical role in the injection principle and in the development of the following processes.

In addition, Agarwal et al., [30] demonstrates that when using three injection pressures (300, 500 and 750 bar) and four different injection starts time, the concentration of the particles rises proportionally when the engine load increases and this it is reduced when the injection pressure increases. This shows the direct influence of the motor and the injection pressure on the number of particle concentration. Diesel engines with high pressure (750 bar) of injection emit a lower quantity of particles and have a better final performance. Having smaller particle sizes helps particle traps reduce emissions and be retained in these traps [46].

Kumar [31] points out in his research at CRDI that at high injection pressures the result, it is a spray with greater penetration and a greater coverage area compared to low pressures in the same period of time. In addition, using the injection start as a comparative parameter, it is observed that the average fuel particle size increases with the delay of the start of the injection. That it is to say, the delay to the injection is a parameter that directly influences the distribution of number and size of the particles [53, 64].

3.2 Polluting emissions by different injection configurations

Regarding emissions, the use of injectors with a greater number of plates and springs allows an injection at higher pressure and with greater range within the chamber. However, this generates emissions of harmful gases without contaminating such as HC. Mane [24] notes that by varying the injection pressure and starting from the emission analysis, the CO_2 content in the emission increases with the increase in injection pressure and load. The NOx content in emission also step up with increasing injection pressure and load on the engine. The emission of CO first decreases as the load increases to a certain level and then begins to increase [52].

At the level of polluting emissions, the injection pressure that it has the lowest percentage of CO_2 is 300 and 400 bar. On the other hand, while the pressures are higher, the CO_2 level reaches its maximum. Thereby, the CO level is reduced when the injection pressure increases and the NOx emission step up according to the injection pressure [22]. Another factor to consider in emissions is the number of holes in the injector. Tumbal et al. [32] performs a comparative analysis of two injectors the one with 6 and the other with 7 holes, these of 0.2 mm in diameter. In polluting emissions such as HC, HSU and CO, it is the 6-hole injector that produces the most pollution. This is seen in the case of NOx, whose highest contamination index, it is carried by the injector with 7 holes. A high vaporization due to the greater number of holes can explain the greater presence of NOx for these cases.

There was an analysis in an engine with common rail, but this time filled with the cooking oil used. The results indicated by Hwang et al. [15] show that the combustion of biodiesel, with respect to diesel in a test of an engine with a cylinder at 160 MPa of injection pressure, started a little later, but with a change of pressure in the cylinder no significant pressure in the cylinder and rate of heat release is lower for biodiesel with 210 J/deg than for diesel with 270 J/deg. The emissions of smoke and CO from biodiesel were lower than those from diesel in almost all operating conditions, but NOx emissions evidently increased for biodiesel, as shown in figure 3. Emissions of HC from biodiesel were slightly lower than those of diesel at the injection pressure of 160 MPa. Smoke and HC emissions were reduced with the increase in injection pressure. This confirms the aforementioned biodiesel data [57].

On the other hand, Hwang et al. [15] marks that the pressure did not have an obvious effect on NOx emissions for diesel, but just the NOx emissions are those that increased dramatically in the pressure of 160 MPa. The NOx values for biodiesel at the highest point is 35 g/kWh, whereas for diesel it is 6 g/kWh. For this, a 160 MPa CRDI engine was used from -25 to 0 degrees crank angle.

3.3 Influence of height on emissions with diesel and biodiesel in engines with CRDI

One of the important factors to consider for the injection is height. In high altitude cities above 2500 meters above sea level in a CRDI system, a greater amount of injected fuel is obtained compared to the injection at sea level. Gastaldi [40] indicates that at 4000 rpm at sea level there is a measurement of approximately 6 mg/stroke and at 2500 meters above sea level 7.5 mg/stroke. This is explained by the lack of air in the height and the compensation that the system makes for this fault. This effect is replicated again in the rail pressures. Although the variation is not greater, there is a greater pressure with respect to the pressure at sea level. However, despite having variations at both the sensor and consumption levels and pressures when comparing operating parameters at sea level and height.

Liu et al. [41] states that the change of inlet oxygen content due to the variation of altitude in the fuel directly affect the performance of the diesel engine. Liu et al. [41] makes a comparative experiment a high-pressure common rail diesel engine powered by pure diesel and biodiesel-ethanol-diesel (abbreviated as BED) combined with an oxygen content of 2%, 2.5% and 3.2% in mass percentage at different atmospheric pressures of 81 kPa, 90 kPa and 100 kPa. As a result, Liu et al. [41] indicates that, in this diesel engine, the emission of soot decreases with the increase in atmospheric pressure and the oxygen content of the fuel. The variation of the oxygen content of the fuel has a more noticeable effect in reducing the emission of soot than the effect of the oxygen content of the intake air affected by the variation in altitude. In addition, the effects of BD and BED fuels with basically the same oxygen content in the full-load performance, fuel economy and emission of soot from the diesel engine is different. The specific fuel consumption of the brake and the emission of soot from the BED fuel are lower than those of the BD fuel.

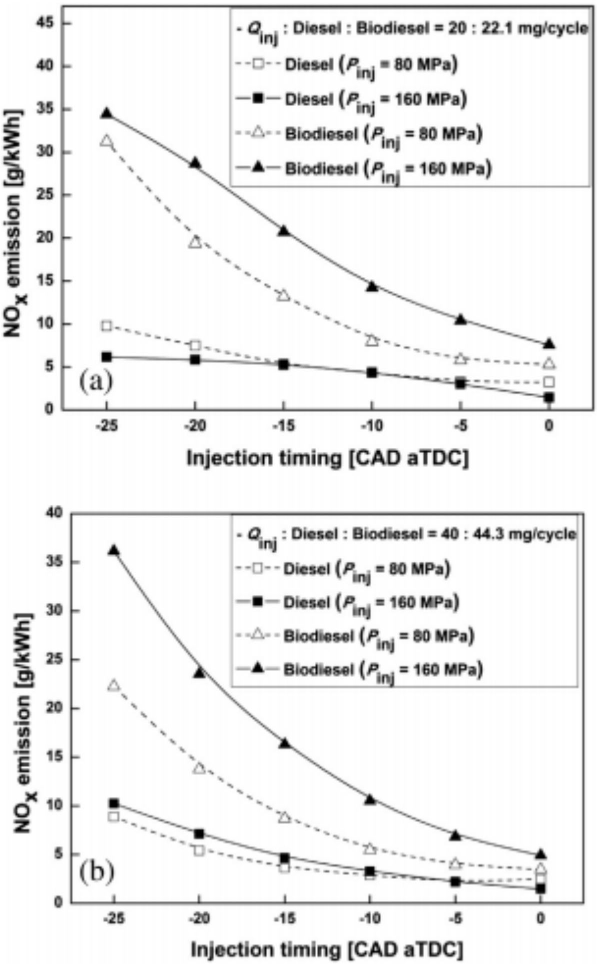

Fig. 3. Comparison of NOx emissions with different injection pressures, timings and loads: (a) low load, (b) high load condition [15].

On the other hand, there is also the use of different fuels to replace the common diesel. The most popular being biodiesel derived from corn and oils [20, 60]. There are also other mixtures for example the one that Ayodhya et al. [42] experiences with a mixture of plastic waste. This is because the plastic remains an element that needs to be recycled due to the large amount of waste that ends up contaminating the planet. In fact, the engine managed to operate with this 30% plastic oil without any modification to the CRDI system. At the level of polluting gases, gases such as CO, HC and soot increase marginally. This is explained by the poor preparation of the mixture to combust. However, a maximum NOX reduction of 36% to 20% was obtained, thanks to the implementation of the EGR. The benefits of this mixture allow the diesel engine to operate without modifications and can be an alternative fuel to reduce the production of fossil fuels [55].

At the same time, biodiesel and bioethanol are added to the mixture. According to Kim and Choi [39], biofuel is considered one of the promises for alternative fuel to reduce oil extraction. In their study they analyze the characteristics of particle size distribution, the reaction characteristics of the nanoparticles in the catalyst and the characteristics of the exhaust emissions when a CRDI engine works with a biofuel mixture. The study yielded interesting results. Among the main ones are the performance of the engine working with the fuel mixture. At the performance level, the result was similar to that achieved with the D100 fuel [39]. This is explained by the low calorific value in the biofuel mixture. At the level of emissions, the biodiesel mixture reduces THC and CO, but the NOx keeps increasing. An important result is the reduction of 50% of smoke emissions [39].

Similarly, the study conducted by Shahir, Jawahar and Suresh [23] also confirms the reduction of particulate matter (PM), HC and CO using biodiesel [62]. And as demonstrated by Kim (2010), a similar performance is obtained when using biofuel, denoting a small loss of power [23]. At the NOx level, the authors confirm this increase by an average of 4 times more with respect to the same analyzes with diesel.

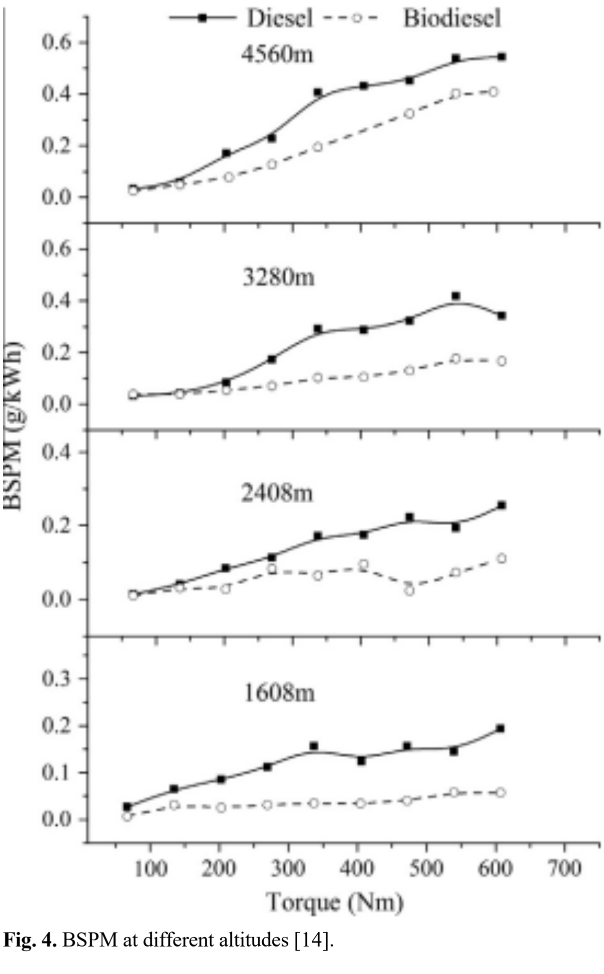

Fig. 4. BSPM at different altitudes [14].

The injectors with better injection delay and a faster injection start, with a much higher initial injection amount are factors to be considered in these types of injectors, especially when working in low oxygen conditions such as in height [10]. An interesting analysis is the effect that height has on engines and combustion. In the study conducted by Yu et al. [14] the increase in altitude has an effect on the start of combustion. It is said that for both biodiesel and normal diesel there is a delay at the start of combustion. As well as a decrease in the portion of premix in combustion. At the level of pollutants, the CO, THC and PM rise with the increase in altitude, as shown in figure 4. However, between diesel and biodiesel, the latter has less pollutants at the same altitude than diesel [54]. It should be noted that at high altitudes, for example over 3000 meters high, the benefits of biodiesel begin to fall mainly at the level of THC and PM. This could be explained due to the low atomization of the fuel with the increase in height. On the part of NOx, there is no observable variation in biodiesel as a function of height [49]. Wang et al. [43] performs another experiment with biodiesel at 4500 meters of height at the level of performance does not present major variations in parameters such as start and duration of combustion, premix level and duration and heating times. The only difference is with respect to the mass flow of exhaust air, which is beneficial in the decrease of air consumption.

Pérez and Boehman [44] indicates that the use of enriched oxygen in a diesel engine under high conditions is analyzed parameters such as fuel injection, engine load and performance parameters such as power output and the maximum rate of heat release. Oxygen enrichment allows to decrease the maximum cylinder pressure that occurs at high altitudes, so the enrichment process helps the cylinder pressure [56]. To extract the maximum fuel combustion energy, the fuel injection time should not be delayed to less than 8.4 AC BTDC and the load should be at least 0.22 MPa (50%).

3.4 Comparison of diesel with biodiesel in the performance of engines with CRDI

In short, biodiesel plays an important role for emissions and as an alternative fuel. Above all, due to the inclusion in the EURO VI category that greatly limits the pollutants that vehicles can emit [47]. When these categories come into force, the plan to improve fuel is an important alternative since the indexes of polluting gases have been decreasing more and more. Currently EURO VI allows 0.50 g/km of CO, 0.17 g/km of HC + CO, 0.08 g/km of NOx and 0.005 g/km of PM for tourism cars in the diesel category [33]. However, biodiesel standards must be met in order for it to work properly as indicated by Mofijur et al. [13] where the biodiesel properties must comply with the ASTM D6751 and EN14211 standards to be used in engines. Thus, biodiesel tends to dissolve the accumulated particles and sediments found in normal diesel. Therefore, modifications must be considered for the use of biodiesel in engines and CRDI systems such as the use of Teflon, nylon, aluminum, stainless steel, glass fiber among others, materials resistant to the effect of biodiesel [13].

For its part, Xue et al. [34] where it indicates that the use of biodiesel leads to a loss of engine power. Similarly, Aalam et al. [35] shows that in its analysis with biodiesel that the HC decreases as well as the CO and as in the other results the NOx increases in a small amount. In the same way, the emission of smoke decreases drastically. The results found by Aalam et al. [45] have a variant that is the addition of aluminum oxide in biodiesel. This addition has better results in the mixture with even higher levels of contaminant decay. These effects of biodiesel with the pollutants emitted are repeated in the experiments carried out by Gangwar et al. [36] and Nedayali and Shirneshan [37] confirming positive factors in the use of this fuel in addition to not being a complete dependent of fossil fuels [61].

Xue et al. [34] indicates that the use of biodiesel leads to a loss of engine power, but also notes that the change is so slight that it is imperceptible during driving [63]. Thus, PM emissions in biodiesel are significantly reduced along with a greater amount of oxygen and less aromatics compounds. This also agrees with the reduction of HC, CO and THC and the increase in NOx caused by the increase in oxygen. So Xue et al. [34]

concludes that biodiesel blends can replace diesel in order to help control pollution without significantly sacrificing engine power and economy by vehicle use. The final result of the experiment carried out by Hwang et al. [15] indicates that the fuel consumption with respect to the injection times of biodiesel is greater than that of diesel under all the above-mentioned experimental conditions, such as pressure, time of injection and the crankshaft variation angle.

For its part, Shahir et al. [23] makes a comparative study of diesel and biodiesel in internal combustion engines with emphasis on emissions. It specifies a section for engines with CRDI where it indicates that Zhang et al. [38] they experiment with some mixtures of soybean biodiesel in a modern engine with CRDI, cooled EGR and VGT. Experiments show that combustion with these biodiesels is associated with NOx growth. Likewise, Kim and Choi [39] report that the BD15ED (15% biodiesel, 5% bioethanol and 80% diesel) decreases THC emissions compared to B20 (20% biodiesel and 80% diesel) in the same engine with rail common. In the same way, Kousoulidou et al. [6] reports that only the RME mixture exhibits a 4% reduction in CO2. This clearly demonstrates the potential benefits of biodiesel fuels. On the other hand, the level of CO if it was found 6 points below the standard.

The HC however grows both for diesel and biodiesel used by Shahir et al. [23], particularly for PME derived from biodiesel reaching a maximum difference of -40%. In contrast, the NOx index continues to hold for both the PME and RME biodiesel. Of course, it is worth clarifying that the PME mix registers 20% more emissions in a general balance.

4. Conclusions

In conclusion, an investigative analysis is made about injection pressures and configurations to find the best configuration and the best performance. In the analyzed studies it has been found that, in the injector, the number of holes, the number of flat springs and the injection pressure are the three factors that have the most influence on the performance of the engine. Similarly, the pressures that have the best results are those between 600 and 800 bar.

At the level of emissions according to certain configuration parameters, having a lower injection pressure (between 300 and 400 bar) it is obtained precisely the lowest percentage of CO2. On the other hand, the number of holes of the injector directly affects elements such as THC, HSU and CO that having more holes the injector reduces these contaminants, if it is not repeated for NOx that has a higher index due to the higher vaporization.

The height has to be a parameter to consider in view that as mentioned by the authors cited, on the 2,500 meters above sea level the CRDI systems begin to consume more fuel due to the lack of oxygen. As a result, an increase in HC, PM and soot is obtained with the increase in altitude. It is also confirmed that the change of inlet oxygen content due to the variation in altitude and the change of oxygen content in the fuel directly affect the performance of the diesel engine.

The inclusion of biodiesel is an alternative, however, pressure parameters should be considered in view that by performing a comparative analysis, at pressures above 1600 bar with the use of biodiesel, the level of NOx increases but in benefit values up to 8 points less in pollutants such as HC, CO and smoke. This is how biodiesel is a fuel alternative to reduce emissions since it shares similar operating parameters with diesel in engines without sacrificing significant power and performance factors.

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