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REVIEW ARTICLE

Exploring the Implementation of 6-Stroke Engine and Biofuel Alternatives Compared to Standard Practice: A Review

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ABSTRACT: In the Paris agreement, the European Union (EU) decided to embark on an energy transition, aiming for decarbonization. In this context, the members agreed on the ban of newly registered Internal Combustion Engine Vehicles (ICEVs), with the goal of the Battery Electric Vehicles (BEVs) becoming predominant. However, this measure threatens all in-paradigm innovations, such as biofuels and the six-stroke engine. These were the main objects of analysis of this review paper. The thorough comparison regarding Net Energy Balance (NEB), price competitiveness, and sustainability between corn, sugarcane, and cellulosic ethanol concluded that sugarcane ethanol poses the best alternative to its fossil fuel counterpart. Regarding the six-stroke engine (specifically the water injection model) in comparison with the four-stroke, numerous benefits of the former stood out, which led to it being chosen as the more efficient and environmentally friendly alternative. These results proved the author's hypothesis partially correct, as it stated the best combination would be of the six-stroke engine with corn ethanol, not sugarcane.

KEYWORDS: Mechanical Engineering, Automotive Biofuels, Ethanol, Internal Combustion Engine Vehicles, Six-Stroke Engine, Sustainability.

Introduction

In present times, the aggravation of the greenhouse effect has led to global warming and climate change. This effect is the imprisonment of heat from solar radiation in certain molecules in the atmosphere, specifically those called greenhouse gases, or GHGs. It is a natural phenomenon, fundamental to the existence of life on the planet. However, the relentless use of, and consequent dependence on, machines and mechanisms for which the main source of energy is fossil fuels has contributed to an unnatural and elevated concentration of GHGs in the atmosphere. Regarding gasoline-fueled emissions, the Short-Lived Climate Forcers (SLCFs), specifically the ozone and methane, have a warming force combined of (+23.2 ± 12.0 mW m^{-2}).[1] Not only does this aggravation in the greenhouse effect impact the environment, but also the health of people, especially in urban centers, where the extended exposure to surface PM2.5 (Particle Matter with 2.5 or less micrometers of diameter) and ozone is linked to cardiovascular and pulmonary diseases, including cancer, which in 2.2 - 2.3% of cases lead to premature deaths.[1] The road transportation sector is responsible for 70% of overall transportation emissions,[2] which account for 23% of the total carbon dioxide (CO_2) emissions worldwide.[3] Therefore, measures need to be taken to lower the GHGs, SLCFs, and other toxic or pollutant gas emissions and, consequently, mitigate the global warming and public health concerns.

With this in mind, the EU Parliament and Commission came to a conclusion to engage in an energy transition among the members, aiming to decarbonize in alignment with the Paris agreement.[2] One of the multiple measures decided was the ban on newly registered ICEVs,[4] as well as the ban on their sales,[5] starting in 2035. Although this transition constitutes a change in the foundation of road transportation, it is estimated that the cost of realizing this alternative will be similar to maintaining the existing system.[2] Therefore, it was suggested to be economically viable and advantageous to engage in the transition. Before the ban, it is essential to phase out high-emitting ICEVs. To effectively accomplish this phasing out, gradual increases in fuel and high registration taxes, as well as subsidies to make low-income consumers' purchase of new, less polluting cars viable, are recommended. In addition, R&D investments in alternative vehicles, to help with social acceptance and support of this change, are encouraged.[2] However, this R&D is focused mainly on new-paradigm innovations. That means discarding the current automotive standard - in this case, the ICEVs - and researching alternatives that do not utilize innovations in existing technologies. Examples of the new-perspective innovations would be the BEVs and the Fuel Cell Electric Vehicles (FCEVs).[6] Nevertheless, new paradigms are not the only or, in many cases, the best option. Though BEVs do not participate in direct emissions of GHGs and SLCFs, they bring complications, i.e., high cost of infrastructure, deficiency of charging stations, range anxiety, and sustainability dependent on the emissions of the power plant that supplied the energy for charging.[7] Hence, it is important to engage in in-paradigm R&D.

This literature analysis paper will bring forward a six-stroke Internal Combustion Engine (ICE) model and biofuels as alternatives to the present condition in the automotive sector. These innovations were chosen due to their capacity to reduce fuel consumption and pollution, while providing an additional power stroke,[8] and having a renewable source.

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■ Discussion

The initial hypothesis for this review was that, considering the present conditions of the ICEVs in comparison to Electric Vehicles (EVs), it is believed that the use of corn ethanol, combined with the Crower six-stroke engine model, will be a more efficient paradigm alternative and have a better impact globally.

Biofuels:

Foremost, the use of biofuels aims to be a sustainable alternative to the use of fossil fuels. There are four generations of biofuels: the first one has edible biomass as feedstock, the second one has non-edible biomass, the third one has seaweed and microalgae as feedstock, and the fourth uses genetically modified organisms.[9] Their sustainability comes from the unique aspect of the biofuel's feedstock: photosynthesis. This process converts luminous energy into chemical energy.[10] It produces glucose out of carbon dioxide and water, and releases oxygen as a byproduct. This capacity is what makes the biofuels sustainable and reduces the GHG emissions, where the carbon released during combustion, generally in the form of carbon dioxide, is consumed by plants, which, later on, become the biofuel. However, first-generation biofuels cannot be carbon neutral and tend to have a lower GHG emissions reduction than second-generation ones, as it inherently requires land use change (LUC), even if indirect.[11] Carbon neutrality is a rather abstract concept, as all of the carbon gases released in combustion can't be consumed by the exact feedstock, in the same proportions as it converts them into glucose. However, it illustrates a cycle of atmospheric carbon sequestration, which is essential to control the aggravation of global warming.

This review took into consideration two different types of first-generation ethanol and a second-generation one: corn ethanol, sugarcane ethanol, and cellulosic ethanol.

Corn ethanol:

The ethanol conversion faces a challenge in dealing with the starch supramolecular structure present in the corn. Figure 1 shows the corn starch molecule, which is turned into glucose. This issue makes it so that additional energy is required to process the starch and turn it into glucose, and put it through fermentation and distillation.[12] Specifically, in the earlier stage of hydrolysis, it is most efficient to produce an enzymatic preparation using genetically modified microorganisms.[13] Understandably, there is an increase in the efficiency of the ethanol production, as well as a cost reduction of the process. Additionally, the production of corn ethanol generates byproducts (such as corn gluten meal, corn husk, and corn steep liquor) which are mostly used as fertilizers, functional foods, or livestock feed, and requires, most of the time, the burning of fossil fuels.[12] However, this secondary use of the byproducts could lead to a reduction of waste pollution in corn processing plants, as well as increase the economic value of corn.[14] Despite this lower net energy gain of corn ethanol and increase in GHG emissions,[15] the widely spread maize production combined with subsidies (in the USA), which bears the high costs for production, and an ethanol yield of 0.3235 L/Kg[16]-in more efficient dry milling processes - creates a condition of economic competitiveness, where the use of corn feedstock leads the American and Global biofuel market.[12]

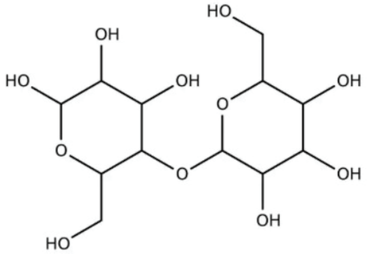

Figure 1: Corn starch molecular structure. Due to the complex structure, additional energy is required to process the starch and turn it into glucose.

However, the use of corn as feedstock for this first-generation biofuel affects the corn market, making the food price more volatile.[17] The increasing ethanol production has an elevating effect on corn prices.[18] However, no interaction between the oil and ethanol markets was registered. The volatility in corn ethanol was not stimulated by volatility in energy prices.[17]

Sugarcane ethanol:

The production of sugarcane ethanol consists of extracting the juice, rich in sucrose, which is fermented and then distilled.[19] Figure 2 illustrates the sucrose molecule, which is responsible for the energetic reserve in the sugarcane. The main byproduct of this process is the bagasse, residue after juice extraction, which, instead of being discarded, is used in steam generation, gasification, pyrolysis, or even as raw material for acidic and enzymatic hydrolysis.[20] The main use for the steam is to generate electricity by expanding it in back-pressure turbines, which drive the milling tandem, and the water and processing pumps.[21] The use of this residual biomass in energy production makes for a practically self-sufficient sugarcane mill, with the bagasse being able to provide up to 91% of the energy consumption.[20] In addition, the development of new technologies makes the use of crushed sugarcane stalks to generate electricity greatly advantageous, supplying 15% of the energy needs of Brazil in 2009.[22]

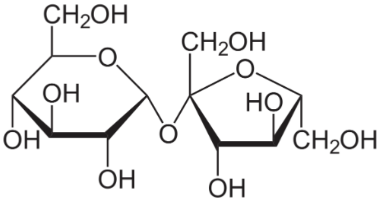

Figure 2: Sucrose molecular structure in sugarcane. Constitutes the main energetic reserve in the sugarcane, and is the feedstock for sugarcane ethanol.

An alternative to bagasse is the use of cane trash, which, with a similar calorific value as the former and a lower moisture content, making it easier to dry,[23] could be used to power steam generation in ethanol plants, making the conversion process more economically feasible.[24] However, there are greater environmental advantages to the on-farm use of cane trash instead of fertilizers, which led to a 82% reduction in the emission of GHGs.[24] Figure 3 shows the use of cane trash in the sugarcane field as a means of edaphic maintenance of the soil.

Figure 3: Cane trash on the sugarcane field. Repurposes cane trash, so there is an increase in soil fertility.

Despite this advantage, the lack of subsidies from the Brazilian government (the largest sugarcane producer) doesn't stimulate sugarcane ethanol production and impedes its further development.[12]

Brazil pioneered the development of sugarcane ethanol in the 70s, with the government's establishment of the ProAlcool movement in 1975.[22,25] This incentive, combined with a past of intensive sugarcane production, led to the development of one of the most efficient systems of conversion of photosynthates into a form of energy.[22] However, since 1990, the Brazilian government has not given subsidies to the sugarcane ethanol industry nor controlled its prices, which has led to a bigger volatility in its price, since the low production costs make its price internationally competitive.[26]

Cellulosic Ethanol:

The cellulosic ethanol has lignocellulosic biomass - that means, energy crops like switchgrass and prairie grasses, or even agricultural residues like corn stover or rice and wheat straw - as feedstock. Figure 4 represents the molecular structure of the lignocellulosic fiber. This type of biomass has low mass and energy densities and requires pretreatment to be utilized in the process of co-fermentation and non-simultaneous saccharification.[27] Nevertheless, the biomass is considered low-input and could be used as an alternative to non-renewable energy in other conversion processes, once it can be grown in marginal lands, and with little to no pesticide and energy input.[15]

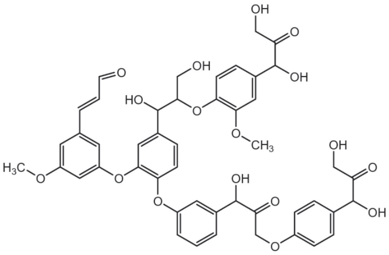

Figure 4: Molecular structure of the lignocellulosic fiber. Despite the complex structure, lignocellulosic biomass is still considered low-input.

Although there are several advantages, this specific biofuel is still in an early research and development stage. An example of new-perspective innovation, as well as in-paradigm, where there would be a significant cost reduction, is the implementation of bioprocessing with cotreatment instead of pretreatment.[28] This process consists of engaging thermophilic bacteria combined with milling while the fermentation is occurring.[28] This innovation, while still speculative, illustrates how there are yet several improvements in the cellulosic conversion process to maximize economic and environmental benefits.[27]

Biofuels comparison:

Ultimately, this comparison will determine which biofuel of the three considered presents high economic competitiveness with the fossil fuel counterpart, while remaining efficient and sustainable. Although the most sustainable of them all, the cellulosic ethanol has an extremely low energy density, which means it will be inefficient in ICEs.[27] In addition, the cost of conversion is too high, in such a way that even with a competitive purchase price of the feedstock, the final price is not yet competitive in the market.[28] These issues discard the cellulosic ethanol as the most effective option. The second alternative is corn ethanol, which has a higher ethanol yield per mass in comparison to sugarcane ethanol.[12] This contributes to it being the most used worldwide. However, it presents an incredibly low NEB, due to the energy, commonly produced by the burning of fossil fuels, required to process the starch in the feedstock.[15] As a result, the conversion of corn ethanol may sometimes produce GHG emissions rather than mitigate them.[12] When considering the LUC, cropland expansions and use of fertilizers, the GHG emissions from the production of corn ethanol are at a minimum, as high as gasoline, or even higher, sometimes increasing emissions by 20% to 50%.[29]

This leads to the third biofuel, sugarcane ethanol. Its costs are 50-60% lower than those of corn ethanol,[12] which makes it a more attractive alternative to underdeveloped locations. Additionally, the sugarcane ethanol conversion process's by-product, used in the energy production of the sugarcane mills, increases its NEB.[20] Finally, as the main source of energy in the conversion process comes from the remains of the feedstock itself, the cycle of carbon neutrality is renewed.

Therefore, the data show it is preferable to choose sugarcane ethanol as a sustainable alternative to its fossil fuel counterparts as fuel for ICEs.

Six-stroke engines:

The majority of automobile manufacturers utilize engines based on the Otto cycle of combustion. The pistons on an engine based on this mechanism have four strokes per cycle.[30] These being:

- intake, where the pistons move, increasing the volume in the combustion chamber, which draws the air-fuel mixture in;
- compression, once the intake valve is closed, the piston compresses the mixture;
- combustion, a spark ignites the compressed mixture, which causes the piston to move, expanding the volume;
- exhaustion, with the exhaust valve open, the piston moves, decreasing the volume, which makes the trapped gases escape.

This pattern means that out of every four strokes, one generates power and moves the crankshaft.[30] The essential difference of the six-stroke engine is that there is an additional power stroke in the cycle. This means the work stroke to number of strokes ratio goes from 1:4 to 1:3, which leads to a smoother running at low speeds.[8,31] In this cycle, there will be two ad-

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ditional strokes, the second power stroke (usually powered by steam or air) and the second exhaust stroke.

However, this is not the only advantage. The six-stroke engine brings an increase in thermal efficiency by 20% and a reduction of fuel consumption by 40% when compared to the four-stroke engine model.[8] Additionally, it shows a 60-90% reduction of the polluting emissions, for example, a 65% reduction in CO (carbon monoxide) production.

Nevertheless, the data represent the general advantages of six-stroke engines. There are several types of six-stroke engine models, which use additional, non-detonating fluids, such as the Crower water injection six-stroke. This specific model takes advantage of the great amounts of dissipated energy (around 75% of the energy lost to friction, coolant, and exhaust gas)[31] in the form of heat to preheat the water and charge amounts of it into the combustion chamber.[32] The two sources of power for the heating of this additional stroke are the engine coolant and exhaust gas. These will heat the water, which will have to be pressurized so as not to boil and to have enough pressure for its injection into the cylinder.[33] This results in an improvement in engine performance, once there is a recovery in the exhaust heat and the waste exhaust heat is partially converted to useful work.[32] Due to the increase in volumetric efficiency, the water injection engine model registered that the fuel consumption increased 2%. However, the specific fuel consumption decreased 9%. This means that 9% less fuel was used to generate the same amount of energy, indicating that the engine is more efficient. Additionally, there was a decrease in the exhaust gas temperature by 7% and in the CO and HC (Hydrocarbon) emissions by 21.97% and 18.23%, until 3000 rpm, respectively.[32] Finally, there was an increase in the power output and in the brake torque by 10% each.[32] Moreover, this engine model is proven to accommodate the use of biofuels, which will become more frequent in the upcoming years.[34]

Ultimately, it becomes evident that the six-stroke engine is extremely beneficial to the development of the automotive industry, as it brings extraordinary efficiency improvements, as well as a reduction in polluting gases, which contribute to the mitigation of global warming effects.

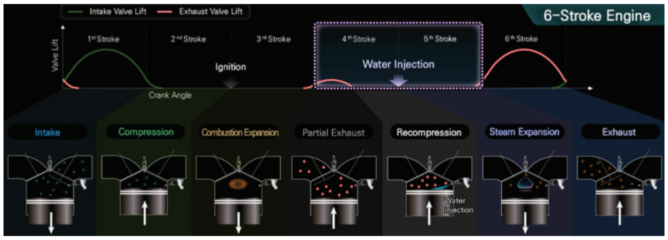

Figure 5: Mechanism of the six-stroke engine cycle using water injection. Illustrates what happens in the combustion chamber stroke-by-stroke in correlation with valve timing.[35]

Figure 5 demonstrates how the strokes of this engine model function in correlation to the valve timing. Firstly, the intake valve is opened, which admits the fuel-air mixture into the combustion chamber as the piston moves down. Then this valve is closed, and the crankshaft pushes the piston upward, increasing the internal pressure. With the mixture extremely compressed, a spark plug ignites the combustion, which moves the piston down. The significant difference to the six-stroke engine starts here in the heat recovery steam expansion cycle, as there is only a partial exhaustion of the gases as the piston moves up. In this same stroke, as the barely open exhaust valve closes, pressurized water is injected into the already hot cylinder, which continues to compress the water.[36] Now, the heat of the chamber turns the liquid pressurized water into steam, which expands the piston downwards, generating a second power stroke with the same power levels as a regular combustion stroke.[31] Finally, all the remaining gases are released as the exhaust valve opens in its entirety. After this stroke, the six-stroke cycle restarts.

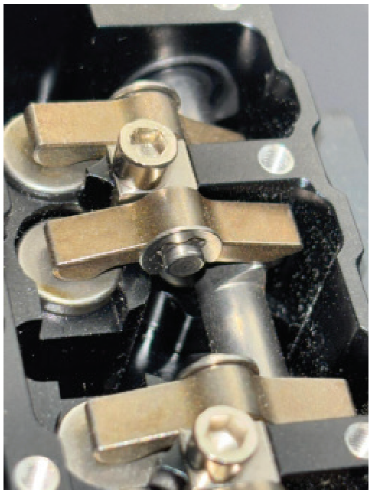

Figure 6: Camshaft from a SEMTO ST-NF2 Inline Twin Cylinder Engine Model. Demonstration of the camshaft mechanism.

These two additional strokes, however, will require some changes to the valve mechanism, specifically to the camshaft, which, with ridges (cams) on it, controls the valve timing. Figure 6 shows the camshaft pushing the rocker arm so it opens and closes the valve according to the desired timing.

Figure 7 illustrates the required modifications from the 4-stroke intake and exhaust cams to the 6-stroke intake and exhaust cams. Both the intake and exhaust cams will need to be modified, as the intervals have shrunk from 90° to 60° each. The exhaust cam will need an additional lobe for the partial opening of the exhaust valve in the Partial Exhaust & Re-compression stroke.[36] In addition, it will be necessary to adjust the gear ratio from the crankshaft to the camshaft.[31] In the four-stroke engine, the crankshaft spins 720° for the camshaft to complete one cycle of 360° (2:1 gear ratio). However, for the six-stroke engine, the crankshaft will have to spin 1080° so the camshaft spins one cycle (3:1 gear ratio).[36] In addition, the camshaft followers will have to change from flat to roller or spherical shape, due to the reduction of the valve opening from 900° to 600°.[31]

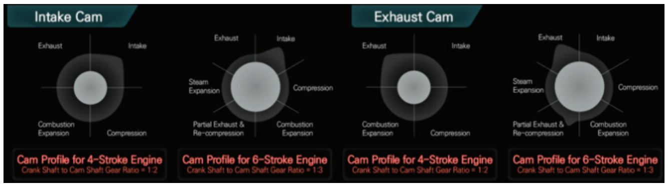

Figure 7: Modification of the cam profile from the four-stroke engine into a six-stroke engine.[35]

In essence, the additional power stroke serves to increase the amount of work the engine does, thus increasing the efficiency and power of the engine itself. This is illustrated by Figure 8, which compares the four-stroke with the six-stroke through a Pressure x Volume diagram, where the area within the lines represents the work done. Comparing the four-stroke engine diagram with the six-stroke engine diagram, there is a significant increase in the work done. This additional work is obtained from the expansion force of the steam generated inside the cylinder.[35]

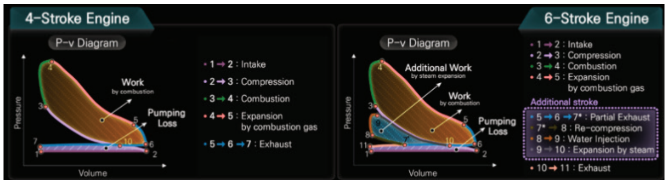

Figure 8: Schematic of the six-stroke engine on a P-V diagram. The six-stroke engine shows a significant increase in the work executed.[35]

Results

The thorough analysis of recent and past literature leads to preferences in the selection of in-paradigm alternatives to the environmentally harmful status quo of the automotive industry. Due to literature investigations regarding bioethanol as an alternative to the fossil fuel counterpart, sugarcane ethanol presents as the most beneficial choice. Although it presents a lower ethanol yield per mass, it has lower production costs, which leads to a more competitive price. Additionally, it has a higher NEB due to the use of its own by-product as fuel for the sugarcane mills. Therefore, aiming to achieve global sustainability, the production of sugarcane ethanol should be scaled. Considering the literature on the opportunity to increase efficiency and sustainability of ICEVs, the six-stroke engine (specifically the Crower engine model) is the most favorable alternative. It has a better efficiency due to the higher work stroke-to-stroke ratio. Moreover, the higher thermal efficiency leads to a lower fuel consumption, which contributes to lower GHG emissions. It's also worth noting that it is possible to use biofuels in this engine. Thus, the choice of a six-stroke instead of a four-stroke is clear. Nevertheless, though minimal, changes to the regular four-stroke engine will have to be made, such as changes in the camshaft and its gear ratio to the crankshaft.

These analyses lead to the main point of this article: the combination of biofuels and the six-stroke engine. Since this is a literature review, no experiments were made to test the applicability of sugarcane ethanol in a six-stroke Crower engine. That said, it is logical that together they are bound to have these benefits added.

Conclusion

In the midst of a global climate crisis, there is an increasing necessity for innovations with the purpose of maintaining the popular accommodation while mitigating negative environmental effects. In this context, this paper aims to reach a viable alternative for the automotive industry's two main players: the four-stroke Otto cycle ICE and gasoline. Therefore, the author of this paper analysed literature on the six-stroke engine and biofuels, as in-paradigm innovations that could be implemented and substitute the more environmentally harmful alternative.

Ultimately, the literature analysis concluded that the six-stroke Crower engine combined with sugarcane ethanol should bring the most benefits as an alternative to the present norm. Yet, there is a gap in the literature concerning the use of bioethanol to fuel a six-stroke engine and its consequences regarding power efficiency and overall applicability.

As a recommendation to future R&D, as a low-input biofuel, cellulosic ethanol has enormous potential to be the best choice concerning sustainability as well as economy. Nonetheless, many improvements and modifications are yet to be developed in order for this opportunity to become viable. The monopoly of petroleum in lieu of sustainable alternatives may delay the full implementation of biofuels, as a complete replacement of fossil fuels is currently not viable.

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