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ALTERNATIVE FUELS FOR DIESEL ENGINES AND THEIR IMPACT ON ENGINE EMISSIONS. A LITERATURE REVIEW

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Abstract: *Today, there is a significant interest in alternative energy sources for vehicles, as a result of continuous concern for the environmental impact and for consumption of the primary energy sources, which are limited. Diesel engines present particularly significant emission like nitrogen oxides, particulate matter, hydrocarbons and black smoke. This paper present a literature review on some alternative fuels for diesel engines, as pure plant oil, biodiesel and compressed natural gas, and their impact on diesel engine emissions.*

Keywords: DIESEL ENGINE, PURE PLANT OIL, BIODIESEL, CNG, EMISSIONS

1. Introduction

Compression ignition (CI) engines are the most popular prime-movers for transportation sector as well as for stationary applications [1]. Global increasing demands for energy, declining fossil fuel reserves, environmental concerns, and rising prices have resulted in a growing interest in the development of alternative renewable energy source [2].

Petroleum reserves are rapidly and continuously depleting at an alarming pace and there is an urgent need to find alternative energy resources to control both, the global warming and the air pollution, which is primarily attributed to combustion of fossil fuels [1].

In order to meet the energy requirements, there has been growing interest in alternative fuels like vegetable oils, biodiesels, biogas, LPG, CNG to provide a suitable diesel oil substitute for internal combustion engine [3].

Biodiesel production is not something new, because the concept of using vegetable oil as fuel dates back to 1895. Rudolf Diesel developed the first diesel engine which has run with vegetable oil in1900. The first engine has run using groundnut oil as fuel [4].

The promotion of biofuels as energy for transportation in the industrialized countries is mainly driven by the perspective of oil depletion, the concerns about energy security and global warming. However due to sustainability constraints, biofuels will replace only 10 to 15% of fossil liquid fuels in the transport sector [5].

Fossil fuels are expected to continue supplying much of the energy used worldwide. Although liquid fuels remain the largest source of energy, their share of world marketed energy consumption is projected to fall from 35% in 2007 to 30% in 2035 (Fig. 1). The decline is due to projected high world oil prices that lead energy users to switch away from liquid fuels when possible [6].

Altough diesel engines are more efficient than gasoline engines of the same power, and this results in lower fuel consumption and thus in lower carbon dioxide emissions [7], the problem associated with the emissions of smoke, PM, sulfur oxide (SO_x), PAHs, and odor from the exhaust of diesel engines has been widely been a concern in many countries [8].

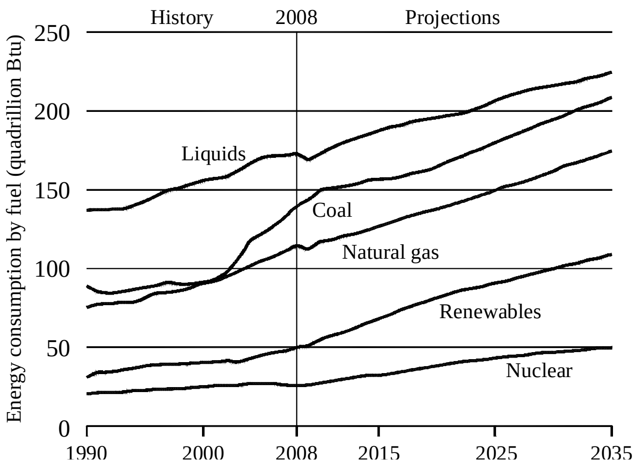

Fig. 1 *World energy consumption by fuel, from 1990 to 2035 [6].*

Diesel engine exhaust is a complex mixture of carbon dioxide, oxygen, nitrogen, nitrogen compounds, carbon monoxide, water vapor, sulfur compounds and numerous low and high molecular weight hydrocarbons, and particulate matter [9].

Exhaust gas emissions of IC engines have been considered a very serious issue regarding air quality and the environment [10] and, therefore, developing and seeking alternative diesel fuels, without modifying engines, has become an important issue [8].

To this context, this paper presents a review of some alternative fuel, like pure plant oil, biodiesel and compressed natural gas, and their impact on diesel engine emissions.

2. Pure plant oil as fuel for diesel engine

As an alternative fuel for compression ignition engines, plant oils are in principle renewable and carbon neutral. However, their use raises technical, economic and environmental issues. A comprehensive and up-to-date technical review of using both edible and non-edible plant oils (either pure or as blends with fossil diesel) in CI engines, based on comparisons with standard diesel fuel, has been carried out [4].

Pure plant oil (PPO), also referred as PVO (Pure Vegetable Oil) or SVO (Straight Vegetable Oil), is the use of plant and vegetable oils without any modification to their chemical structure as a fuel to be combusted inside a diesel engine. This method should not be confused with biodiesel, which is a fuel derived from pure plant oils through a transesterification process that splits fatty acids from glycerin to reduce the viscosity of the pure plant oil similar to that of mineral diesel [11].

Vegetable oils represent a ready, renewable and clean energy source that has shown promise as a substitute to petroleum diesel fuel for diesel engines. There are different ways of utilizing vegetable oils as a substitute for petroleum diesel: (i) crude or refined neat oil; (ii) mixture of oil with diesel fuel with appropriate dilutions; and (iii) alkyl ester products from the transesterification process [12].

Since the most of European biodiesel is made from vegetable oil, this has led to a rapid increase in demand, with a significant impact on European vegetable oil markets [13].

Because the population is constantly growing and also food need is increasing, it is important to focus our attention on non-edible crops. Non-edible oils are not suitable for human food due to the presence of some toxic components in the oil [14].

As indicated by Table 1, numerous plant oils have been tried in diesel engines at some time or other. Relatively few, however, have been systematically evaluated and used [4].

Table 1: *Potential edible and non-edible plant oils for use in CI engines [4].*

Edible oil	Non-edible oil
Sunflower oil, Rapessed oil, Rice oil, Soybean oil, Coconut oil, Corn oil, Palm oil, Olive oil, Pistachia Ol, Sesame seed oil, Peanut oil, Poppy oil, Safflower oil	Jatropha oil, Karanji or Pongamia oil, Neem oil, Jojoba oil, Cottonseed oil, Deccan hemp oil, Kusum oil, Orange oil, Rubber seed oil

Advantages of non-edible crops are ready availability, renewability, higher heat content, lower sulfur content, lower aromatic content and biodegradability, adaptability of cultivating non-edible oil feedstock in marginal land and non-agricultural areas with low fertility and moisture demand, eliminate competition for food and feed [14].

There are 350 species of oil-producing plants and thousands of sub-species [15]. Table 2 gives the average annual oil yield for the common oil plants cultivated in Europe.

Table 2: *Oil producing crops in European Union [adapted from 13]*

Oil producing crops in European Union	kg oil/ hectare
Corn	145
Oat	183
Cotton	273
Hemp	305
Linseed	402
Pumpkin seed	449
Sunflower	800
Rapessed	1000
Olive tree	1019

Diesel engines are designed to burn diesel fuel, which has a lower viscosity than vegetable oil. Therefore the direct usage of pure plant oil in the engine leads to poor fuel atomisation and incomplete combustion, which can rapidly damage the engine. Pure vegetable oil thickness is the central problem for their use since it is 11–17 times thicker than conventional fuel [11].

In the process of converting an engine, adaptations may need to be made to the fuel lines, combustion chamber and fuel injectors. The engine modifications necessary to run a diesel engine with vegetable oils can be divided into two categories: one tank systems and two tank systems. The best way is to fit a professional kit to the diesel engine which includes replacement injectors and glow plugs optimised for vegetable oil, as well as fuel heating [16,8].

The major components of a professional kit are: electrical switching unit (switching to the gas, rinse/ventilation) and an integrated heater (Diesel-Therm), control electronics (diesel - quick rinse, warning when off on vegetable oil), heat exchanger for water / oil circuit, fuel lines, fuel filter, cockpit panel for plant oil / diesel with LED's all operating conditions signal and audible warning when off mode in vegetable oil, complete manufactured cable set with relay sockets, plugs and fuses, various small material (hose clamps), detailed installation manual [17].

With two-tank PPO kits (Fig. 2), one tank holds the vegetable oil and the other petro-diesel (or biodiesel). The engine is started on the petro-diesel tank and runs on petro-diesel for the first few minutes while the vegetable oil is heated to lower the viscosity [11].

Items "O" and "N" represent the two tanks, which are installed inside a vehicle. Heating systems include "M" which is a heater located inside in the vegetable oil tank and "E" which is normally a special type of heat exchanger. The operation of this system is that upon shut down of the engine the mineral diesel or biodiesel from the smaller tank "O" is feed into the engine until all the vegetable oil is purged out [11].

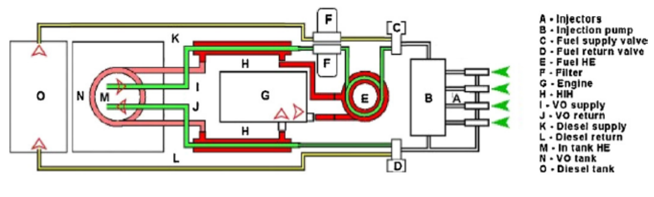

Fig. 2 *Illustration of a two tank system, which allows a vehicle to run on PPO [11].*

Literature on using vegetable oils as fuel for diesel engine shows that exhaust gas temperature and smoke intensity may either increase or decrease in comparison to fossil diesel.

Wang et al. [18] carried out a series of experimental tests to evaluate the performance and gaseous emission characteristics of a diesel engine when fuelled with vegetable oil and its blends of 25%, 50%, and 75% of vegetable oil with ordinary diesel fuel separately. The engine works at a fixed speed of 1500 rpm, but at different loads respectively, i.e. 0%, 25%, 50%, 75% and 100% of engine full loads. The experimental results show that power output and fuel consumption are comparable to diesel when fueled with vegetable oil and its blends. The emission of nitrogen oxides (NO_x) from vegetable oil and its blends are lower than that of pure diesel fuel. This emission character found in the tests to some extent is of significance for the practical application of vegetable oil to replace ordinary diesel fuel.

A technical review and life-cycle analysis [4] revealed that when the engine runs on plant oil, emissions of CO and HC may either increase or decrease (Fig. 3). At low load operation using plant oil, CO emission is almost the same as for fossil diesel. Whereas at higher loads, the mixture becomes richer thus more CO is produced due to the lower oxygen content of plant oil. Emissions of NO_x tend to increase with the nitrogen content of the oil. Most literature reports a decrease in NO_x emission with plant oil (or blends) compared to fossil diesel (Fig. 3).

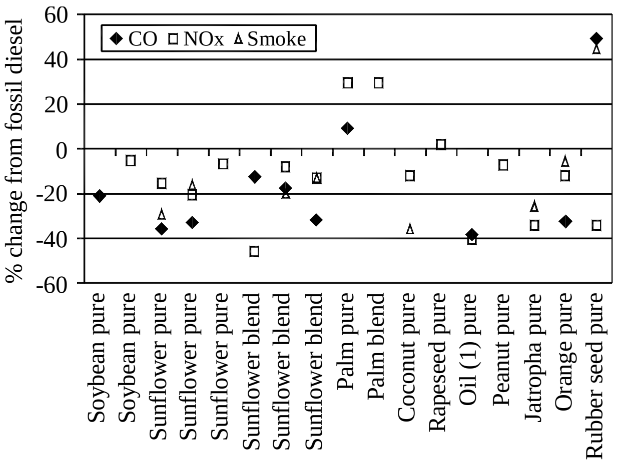

Fig. 3 *CO, NO_x and smoke emission of CI engines running on plant oil (or blends with fossil diesel) as compared to fossil diesel (Oil (1): unknown) [4].*

One can observe that the CO emitted by all biodiesel blends of various origins is lower than that by the corresponding neat Diesel fuel case, with the reduction being higher the higher the percentage of the biodiesel in the blend [19].

Emissions of NO_x tend to increase with the nitrogen content of the oil. The NO_x emissions were slightly reduced with the use of biodiesel or vegetable oil blends of various origins with respect to that of the neat Diesel fuel, with this reduction being higher the higher the percentage of biodiesel or vegetable oil in the blend [4,19].

The smoke density was significantly reduced with the use of biodiesel blends of various origins with respect to that of the neat Diesel fuel, with this reduction being higher the higher the percentage of biodiesel in the blend. On the contrary, it was increased with the use of vegetable oil blends of various origins, with this increase being higher the higher the percentage of vegetable oil in the blend [19].

In other experiment [20], Rakopoulos et al. have evaluated the use of sunflower, cottonseed, corn and olive straight vegetable oils of Greek origin, in blends with diesel fuel at proportions of 10 vol.% and 20 vol.%, in a six-cylinder, turbocharged and after-cooled, heavy duty, direct injection, Mercedes-Benz diesel engine.

Fig. 4 shows, for the speed of 1500 rpm, the emitted nitrogen oxides (NO_x) for the neat diesel fuel, and the 10% and 20% blends of the four vegetable oils with diesel fuel, at the three loads. One can observe that the NO_x emitted by all vegetable oil blends are equal or slightly higher than the ones for the corresponding diesel fuel case, with this increase being higher the higher the percentage of the vegetable oil in the blend [20].

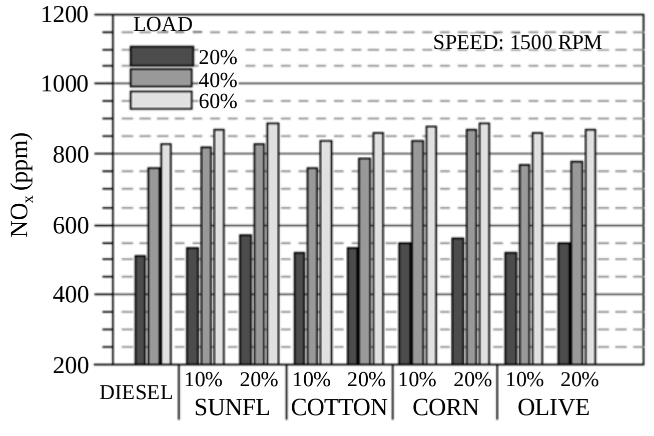

Fig. 4 *Emissions of nitrogen oxides (NO_x) for neat diesel fuel, and the 10% and 20% blends of the four vegetable oil with diesel fuel [20].*

For the same experiment [20], it can be observed that the soot emitted by all vegetable oil blends is lower than the ones for the corresponding neat diesel fuel case, with this reduction being higher the higher the percentage of the vegetable oil in the blend. This is attributed to the combustion being mixing controlled for these vegetable oil blends, as it is also the case for the neat diesel fuel case, which is however now assisted by the presence of the fuel bound oxygen even in locally rich zones [20].

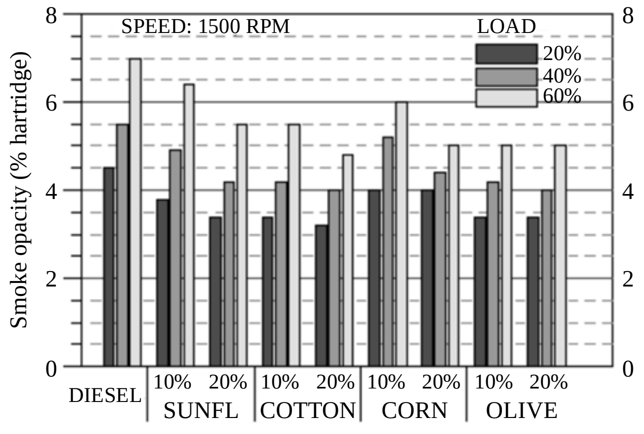

Fig. 5 *Emissions of smoke for neat diesel fuel, and the 10% and 20% blends of the four vegetable oil with diesel fuel [20].*

3. Biodiesel

Crude vegetable oils are inferior as fuel in terms of viscosity, heating value, freezing point, etc. [21]. In order to reduce viscosity, vegetable oils are converted into esters by transesterification

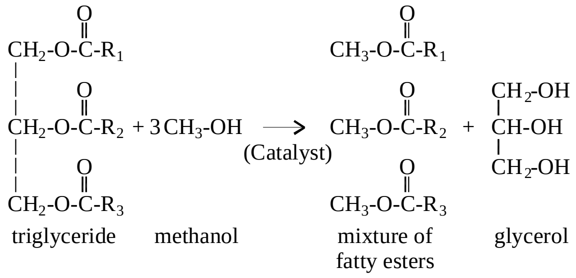

Fig. 6 *Transesterification reaction [22].*

reaction [1]. The result of transesterification reaction (Fig. 6) is biodiesel, as a fuel comprised of mono-alkyl esters of long chain fatty acids derived esters from vegetable oils or animal fats, designated B100 [23].

Because the biodiesel viscosity is almost twice higher than the diesel fuel viscosity (according to Standard EN 14214:2003, the biodiesel viscosity at 40°C is 3.5-5.0 mm^2/s [24]), biodiesel is currently used in blends with diesel fuel.

Biodiesel can be produced from various vegetable oils, waste cooking oils or animal fats. The fuel properties of biodiesel may be changed when different feedstocks are used [25]. However, biodiesel production is highly dependent on many local variables such as feedstock and land availability, costs associated with feedstock procurement, government subsidies and tax reductions as well as interactions with the food industry [26].

The main stages of the fuel systems for biodiesel from vegetable oil and waste cooking oil are shown in Figure 7.

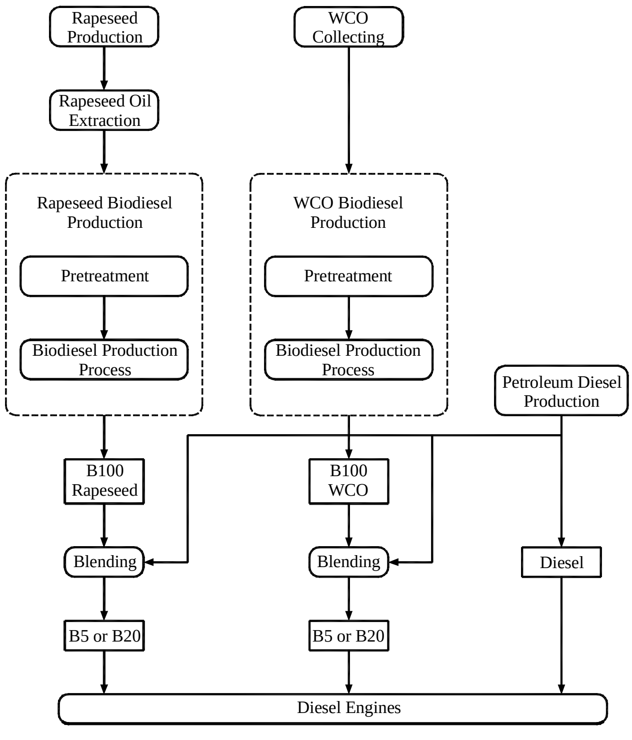

Fig. 7 *Fuel systems for biodiesel from vegetable oil (rapeseed oil) and waste cooking oil (WCO) (adapted from [26]).*

A survey on 27 literatures [27], to study the effect of pure biodiesel on engine power, showed that 70.4% of them agreed that, with biodiesel (especially with pure biodiesel), engine power will

Table 3: *Statistics of effects of pure biodiesel on engine performances (adapted from [27])*

	Total number of references	Increase	%	Similar	%	Decrease	%
		Number		Number		Number	
Power performance	27	2	7.4	6	22.2	19	70.4
Economy performance	62	54	87.1	2	3.2	6	9.7

drop due to the loss of heating value of biodiesel (Table 3). However, the results reported show some fluctuation. Some authors found that the power loss was lower than expected (the loss of heating value of biodiesel compared to diesel) because of power recovery.

Due to the increasing interest in the use of biodiesel, the Environmental Protection Agency (USA) has conducted a comprehensive analysis of the emission impacts of biodiesel using publicly available data [28]. This investigation made use of statistical regression analysis to correlate the concentration of biodiesel in conventional diesel fuel with changes in regulated and unregulated pollutants. Since the majority of available data was collected on heavy-duty highway engines, this data formed the basis of the analysis. The average effects are shown in Figure 8. One may observe that due to higher content of oxygen in biodiesel, CO, PM and HC emission are reduced, but the NO_x emission is higher than that of diesel fossil fuel.

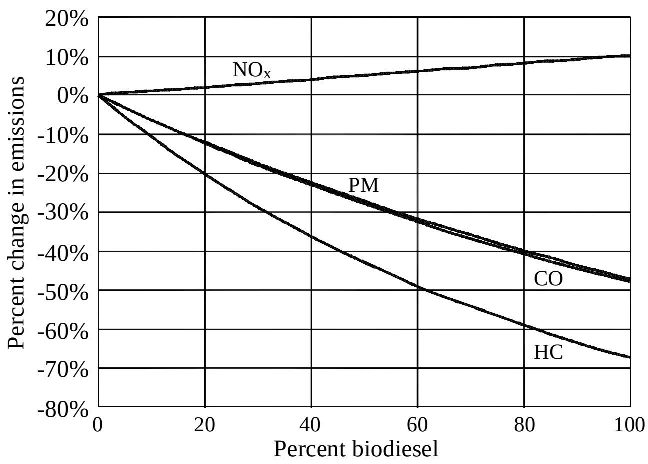

Fig. 8 *Average emission impacts of biodiesel for heavy-duty highway engines [28].*

The results of an experimental investigation [29], using two different samples of B10 blend of eucalyptus biodiesel, showed that smoke opacity improves for both samples, smoke is found to be 64.5% and 62.5% cleaner than that of diesel. Out of all blends B10 was found to be a suitable alternative to conventional diesel fuel to control air pollution without much significant effect on engine performance.

As for the vegetable oils as alternative fuel for diesel engines, the literature on biodiesel emission is not uniform.

In this respect, some available results of Light-Duty diesel vehicle test data for some rapeseed biodiesel blends (a minimum of 20 measurements of a particular blend were required to assess the significance of the effect) allow one to explore the differences in the effects on emissions of the different biodiesel feedstocks [30]. The emission data are discussed as follows:

- HC lower for B20 and B100, but no correlation between biodiesel content in the blend and level of HC emission;
- NO_x higher than for diesel fuel for all blends, the higher content of biodiesel, the higher NO_x emission;
- CO emission is random, lower for B20, but higher for B30;
- Particulate matter (PM) emission is not significant versus diesel fuel. However, a very slight increase of PM for biodiesel blends is observed.

The heterogeneous and uncorrelated data from [27] could be due to the use of biodiesel and biodiesel blends on diesel engines tuned only for pure diesel fuel or for B5-B7 blends. Using higher percentage biodiesel blends, or even B100 fuel, on existing unmodified engines, could cause an inappropriate response of the engine in respect of torque (power) and emission.

4. CNG as fuel for diesel engine

International communities are seeking reliable and alternative fuel sources and technologies to reduce environmental stresses, air pollution, increase fuel availability, decrease the use of and dependence on foreign oil, and optimize the performance of existing fuel supply infrastructures [31].

Natural gas (NG) is one of the most important energy carriers today because it is available in large quantities and its reserves are of the same magnitude as the crude oil reserves [32]. The use of natural gas as a fuel has garnered considerable interest since the beginning of the 1990s.

Italy was the first country in which the use of natural gas as fuel for the propulsion of road vehicles was successful [33]. In the last decade the number of NG vehicles has risen to over a million in several countries around the globe. One reason for this evolution is economic: in many countries NG is considerably less expensive than conventional fuels such as gasoline and diesel. The other advantage is the fact that natural gas burns in a cleaner, less polluting way. Natural gas sources are spread throughout the world, which reduces the risk of an energy crisis [32].

CNG/NG, is a mixture of hydrocarbons in gaseous form, consists of approximately 80-90% of methane along with some percentage of ethane, propane, nitrogen [34]. A gaseous form of natural gas, clearly has some substantial benefits compare to petrol and diesel.

According to [32], the main constituent of NG is methane (80–98%, depending on the extraction source). Other (about 2%), butane and pentane (less than constituents are ethane (1–8%), propane 1%). NG also contains nitrogen and carbon dioxide (0.2–1.5%) and small quantities of sulfur compounds (hydrogen sulphide and mercaptans). Of all hydrocarbon compounds used as motor fuels, methane has the highest knock resistance [32]. Its octane number is ca. 130. NG is non-toxic, odourless and non-corrosive. It is lighter than air and is slightly soluble in water.

Amrouche et al. [35] have found that CNG:

- Is composed of 85 to 99% methane;
- Has the highest energy/carbon ratio of any fossil fuel, and has a high octane (110/130) (against 95 and 98 for gasoline and 92/96 for the diesel). His feature helps the increase of the compression ratio engines and thus the efficiency;
- Is safely: It is lighter than the air, in the case of gas leak, it goes to the atmosphere;
- Auto-ignite above 540°C (450°C for LPG, 220°C for unleaded gasoline and 225°C for diesel).
- Doesn't freeze until below -165°C, which makes it insensitive with the climatic conditions.

One of the reasons to use NG as an alternative fuel was the ecological consideration [32], NG having the potential to mitigate CO_2 emissions due to its lower carbon content [36].

Natural gas is used as a fuel in two forms [32]:

1. In its gaseous form (at ambient temperature and under a high pressure of 20 MPa) it is called compressed natural gas (CNG).
2. In its liquid form (cooled to a temperature of -161°C at atmospheric pressure) it is called liquefied natural gas (LNG).

In the case of using CNG, vehicle engines should be modified (dedicated/retrofitted) at the same time with changing fuels [36]. Dedicated vehicles are preferable but there are a few light-duty CNG vehicles available. For applying to a specific type of vehicle, retrofitting is an option. However, the efficiency of retrofitted vehicles is questionable on reduction of CO_2 emissions [36].

In order to ensure smooth transportation life cycle and sustainability, it is important to synchronize CNG fuel supply, CNG refueling stations and CNG fuel vehicles [31]. Recent studies show that the proper implementation with reasonable ratio of refueling stations to alternative fuel vehicle is of great importance [31].

Many investigations were carried out in order to use of CNG as an alternative fuel according to their fuel usage and they are [34]:

- Dual fuel: like the CNG buses the mixture of CNG and diesel introduced in the engine. As natural gas will not ignite under combustion chamber alone so diesel is required.
- Bi-fuel: like cars and light motor vehicle, convention petrol engine where the fuel system has been modified to operate either petrol gas.
- Mono-fuel: this is specialized engine type which has been designed and optimized to operate only on natural gas.

The natural gas vehicle is currently one of least polluting vehicles available on the market [35]. In fact, compared to others vehicles powered with petroleum products, the CNG vehicles have shown a very strong reduction of the polluting emissions (-100 % of lead, the Non-Methane Hydrocarbons are reduced by approximately 50%, - (50-87%) of NO_x, - (20-30%) of CO_2, - (70-95%) of CO. And the combustion of natural gas produces almost no fine particulate matter). Natural gas vehicles have significantly low noise levels and engine vibration, it reduce noise about -5 to -8 decibels by vehicle [35].

Introducing vehicles that run on CNG can significantly reduce black carbon emissions from on-road vehicles [37].

The use of natural gas as a vehicle fuel is claimed to provide several benefits to engine components and effectively reduce maintenance requirements [34]. It does not mix with or dilute the lubricating oil and will not cause deposits in combustion chambers and on spark plugs to the extent that the use of petrol does, thereby generally extending the piston ring and spark plug life. In diesel dual-fuel operation evidence of reduced engine wear is reported, leading to expected longer engine life [34].

Development of the CNG dual-fuel turbocharged CI engine was described in reference [32]. NG was introduced into the engine cylinder in the gaseous state through a honeycomb mixer. The pilot ignition fuel was diesel fuel. The following results on emissions were obtained (Fig. 9):

- An increase in pilot diesel fuel extends the lean burning limit and decreases HC and CO emissions (while NO_x emissions increase), which is generally higher than for diesel fuelling.
- Smoke emission is considerably reduced for dual fuelling.
- NO_x emission is also reduced.

5. Conclusions

To meet the energy requirements and environmental concerns, there has been growing interest in alternative fuels like vegetable oils, biodiesel and CNG to provide a suitable diesel oil substitute for internal combustion engine.

As an alternative fuel for compression ignition engines, plant oils are in principle renewable and carbon neutral, but their use raises technical, economic and environmental issues.

There are different ways of utilizing vegetable oils as a substitute for petroleum diesel: (i) crude or refined neat oil; (ii) mixture of oil with diesel fuel with appropriate dilutions; and (iii) alkyl ester products from the transesterification process.

Since diesel engines are designed to burn diesel fuel, which has a lower viscosity than vegetable oil, using only vegetable oil as fuel needs to fit a professional kit to the diesel engine, which includes replacement injectors and glow plugs optimised for vegetable oil, as well as fuel heating.

Literature on using vegetable oils as fuel for diesel engine shows that CO emission is decreasing, while emissions of NO_x tend to increase.

To reduce the viscosity of vegetable oils, vegetable oils are converted into esters by transesterification reaction. Because the biodiesel viscosity is almost twice higher than the diesel fuel viscosity, biodiesel is currently used in blends with diesel fuel.

Using pure biodiesel, engine power drops due to the loss of heating value of biodiesel. In some cases, the power loss was lower than expected because of power recovery.

Due to higher content of oxygen in biodiesel, CO, PM and HC emission are reduced, but the NO_x emission is higher than that of diesel fossil fuel.

One of the reasons to use natural gas as an alternative fuel was the ecological consideration, NG having the potential to mitigate CO_2 emissions due to its lower carbon content.

In the case of using CNG, vehicle engines should be modified at the same time with changing fuels. Dual fuel, bi-fuel or mono-fuel fuel systems have been designed and optimized to allow diesel and spark ignition engines to operate only on natural gas.

Compared to others vehicles powered with petroleum products, the CNG vehicles have shown a very strong reduction of the polluting emissions.

The use of natural gas as a vehicle fuel is claimed to provide several benefits to engine components and effectively reduce maintenance requirements .

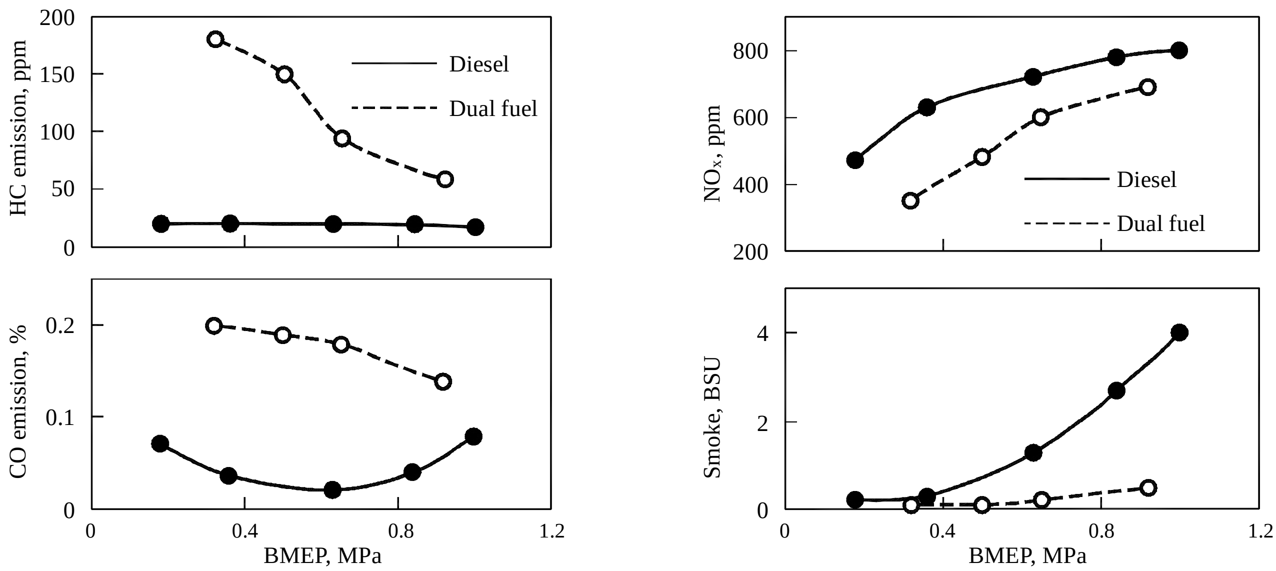

Fig. 9 *HC, CO, NO_x and smoke emissions versus b.m.e.p. for dual and diesel fuelling of a turbocharged engine at n=1600 r/min [32].*

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