Applied Thermal Engineering 29 (2009) 1887–1892

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Review

Determination of ecological efficiency in internal combustion engines: The use of biodiesel

Christian Rodriguez Coronado *, João Andrade de Carvalho Jr., Juliana Tiyoko Yoshioka, José Luz Silveira

São Paulo State University, Campus of Guaratinguetá, Av. Ariberto Pereira da Cunha, 333, CEP 12516-410, Guaratinguetá, SP, Brazil

ARTICLE INFO

Article history:
Received 24 September 2007
Accepted 30 October 2008
Available online 11 November 2008

Keywords:
Ecological efficiency
Engine
Biodiesel
Vehicular fuels
Combustion

ABSTRACT

This paper evaluates and quantifies the environmental impact from the use of some renewable fuels and fossils fuels in internal combustion engines. The following fuels are evaluated: gasoline blended with anhydrous ethyl alcohol (anhydrous ethanol), conventional diesel fuel, biodiesel in pure form and blended with diesel fuel, and natural gas. For the case of biodiesel, its complete life cycle and the closed carbon cycle (photosynthesis) were considered. The ecological efficiency concept depends on the environmental impact caused by CO_2, SO_2, NO_x and particulate material (PM) emissions. The exhaust gases from internal combustion engines, in the case of the gasoline (blended with alcohol), biodiesel and biodiesel blended with conventional diesel, are the less polluting; on the other hand, the most polluting are those related to conventional diesel. They can cause serious problems to the environment because of their dangerous components for the human, animal and vegetable life. The resultant pollution of each one of the mentioned fuels are analyzed, considering separately CO_2, SO_2, NO_x and particulate material (PM) emissions. As conclusion, it is possible to calculate an environmental factor that represents, qualitatively and quantitative, the emissions in internal combustion engines that are mostly used in urban transport. Biodiesel in pure form (B100) and blended with conventional diesel as fuel for engines pollute less than conventional diesel fuel. The ecological efficiency for pure biodiesel (B100) is 86.75%; for biodiesel blended with conventional diesel fuel (B20, 20% biodiesel and 80% diesel), it is 78.79%. Finally, the ecological efficiency for conventional diesel, when used in engines, is 77.34%; for gasoline, it is 82.52%, and for natural gas, it is 91.95%. All these figures considered a thermal efficiency of 30% for the internal combustion engine.

Contents

* Corresponding author. Tel.: +55 12 3123 2814; fax: +55 12 3123 2835.
E-mail addresses: christian@feg.unesp.br (C.R. Coronado), joao@feg.unesp.br (J.A. de Carvalho Jr.), julianayoshioka@yahoo.com.br (J.T. Yoshioka), joseluz@feg.unes.br (J.L. Silveira).
URL: http://www.feg.unesp.br/gose (C.R. Coronado).

doi:10.1016/j.applthermaleng.2008.10.012

1. Introduction

The environmental protection is one of the most frequent problems; nowadays, the reduction of the pollutant indicators of toxic substances in the environment, produced by the industrial and the automotive transportation sectors, is one of the most important targets that are being taken into account in the majority of the industrialized countries. It is necessary that both sectors adopt future strategies for the reduction of pollutants emissions to the atmosphere, with the purpose of reducing the dangerous concentrations in the air.

In the last three decades, the world has been confronted with energy crises due to the decrease of fossil resources, with the increase of environment constraints, and the prices of oil. This situation brought as consequence the search of alternatives and renewable fuels, which have to be not only sustainable, but also friendly in respect to environment and techno-economically competitive. Bio-fuels like ethanol, vegetable oil, biomass, biogas, synthetic fuels, biodiesel, etc.; are starting to be of high interest to the developed countries. Some of these fuels could be used in a direct form; however, others need some kind of modification to replace the conventional diesel fuel – gasification or digestion when the subject is biomass, and transesterification when it is biodiesel.

About 700 million tons of carbon monoxide, 150 million tons of nitrogen oxides, 200 million tons of solid particles, and 200 million tons of sulphur dioxides are released annually in the atmosphere. The majority of these substances are produced by the transport sector. Currently, the internal combustion engines (ICE) produce about 85% of the energy consumed in the planet, for which the vehicles engines constitute a large portion. The exhaust gases that contain toxic substances represent the most dangerous risks related to the environment pollution [1].

The methodology proposed in this paper analyzes the efficiency in internal combustion engines from the ecological point of view, for the separate concentrations of pollutants (CO_2, SO_2, NO_x *and* PM). The ecological efficiency parameter (ε) was considered for steam cycles that use coal [2]; it was extended for combined cycle plants that use natural gas, internal combustion engines and advanced cycles that use biomass as fuel [3]. The ecological efficiency evaluates the environmental impact caused by the emissions in ICE's, per kg of fuel, and not for the amount of released gases in the generation of a power unit.

2. The equivalent carbon dioxide

The coefficient for the equivalent carbon dioxide $(CO_2)_e$, a hypothetical pollutant concentrations factor, is determined by Eq. (1) [2,4]. For the calculation of this coefficient, the maximum allowed value for the CO_2 concentration is divided by the corresponding air quality standard for NO_x, SO_2 and PM in 1 h. The expression for $(CO_2)_e$ is:

$$(CO_2)_e = (CO_2) + 80(SO_2) + 50(NO_x) + 67(PM) \quad (1)$$

In Eq. (1), $(SO_2)_e = 80(SO_2)$ is the sulphuric dioxide equivalent in (CO_2), $(NO_x)_e = 50(NO_x)$ is the nitrogen dioxide equivalent in (CO_2), and the particulate matter equivalent in (CO_2) is $(PM)_e = 67(PM)$. The best fuel from the ecological standpoint is that which presents a minimum amount of $(CO_2)_e$ obtained from its burning. In order to quantify this environmental impact, the "pollutant indicator" (Π_g) is defined by Eq. (2).

$$\Pi_g = \frac{(CO_2)_e}{Q_i}, \quad (2)$$

where $(CO_2)_e$ is taken in kg/kg (kg per kg of fuel), Q_i is the fuel low heating value (LHV), expressed in MJ/kg, and Π_g is expressed in kg/MJ.

3. Ecological efficiency

The ecological efficiency is defined as an indicator which allows the evaluation of thermoelectric power plant performance in respect to pollutants emissions, by comparing the hypothetically integrated pollutant emissions (CO_2 equivalent emissions) to the existing air quality standards. The conversion efficiency is also considered a determining factor on the specific emissions, expressed by a fraction number. Eq. (3) can be used for the determination of ecological efficiency [2,4–6]:

$$\varepsilon = \left[\frac{0.204n}{n + \Pi_g} Ln(135 - \Pi_g)\right]^{0.5}, \quad (3)$$

where "ε" comprises, in a single coefficient, the aspects that define the thermoelectric unit environment impact intensity, fuel composition, combustion technology, pollutant indicator and thermodynamic efficiency. "ε" is directly proportional to the thermoelectric power plant efficiency (η), inversely proportional to Π_g, the pollutant indicator value, and also is located between 0 and 1, similar to the thermoelectric efficiency. The situation is considered unsatisfactory from the ecological point of view when $\varepsilon = 0$; however, $\varepsilon = 1$ indicates an ideal situation from the point of view of energetic efficiency. According to the fuel classification, pure hydrogen would have 0% of impact in the environment, while sulphur would cause 100% of impact; see Table 1 for details.

4. Methodology

Ecological efficiency values for internal combustion engines for the case of urban transport are calculated for different fuels: diesel fuel, gasoline (blended with anhydrous ethyl alcohol (anhydrous ethanol)), biodiesel (B100 and B20), and natural gas. The chemical composition of reactants and products will be used to analyze the fuels.

Gasoline engines (Otto cycle) operate with $12 \leqslant A/F$ ratio $\leqslant 18$ [7]; on the other hand gasoline engines operate with an equivalence ratio (α) between $0.8 \leqslant \alpha \leqslant 1.3$ [8], showing that the gasoline engine operates perfectly in lean, stoichiometric and rich burns. Therefore, this work will consider 30% of air excess for the gasoline fuel and ethyl alcohol fuel. Unlike the Otto engines, diesel engines always operate with a significant excess of air (lean burn, $\alpha > 1$). Diesel engines operate with $12 \leqslant A/F$ ratio $\leqslant 70$ [7]; therefore, the excess of air for diesel fuel was considered here to be 100%. Natural gas also can be burned in Otto engines. An excess of air of 40% is recommended [9]. On the other hand, an equivalence ratio in the range $1.46 < \alpha < 1.64$ is recommended for methane [10]. Therefore,

Table 1
Fuel virtual characteristics [6].

Fuel	S (%)	CO_2 (kg/kg fuel)	Q_i (MJ/kgf)	Π_g (kg/MJ)	ε
Hydrogen	–	0	10,742	0	1
Sulphur	100	1400	10,450	134	0

Table 2
Combustion products (mass percentage).

Products (%)	Alcohol	Diesel	Gasoline*	Nat. gas	B20	B100
CO_2	15.136	10.058	15.037	11.272	10.235	10.943
H_2O	9.288	4.458	7.385	8.756	4.392	4.129
N_2	70.622	74.206	72.494	73.583	74.110	73.724
O_2	4.954	11.278	5.085	6.389	11.263	11.204

* Gasoline with 20% of alcohol.

the excess of air will be considered here to be 40% for natural gas fuel.

In spite of being a toxic gas, CO is not considered a greenhouse gas. Therefore, this gas was not taken into account in the calculations in this paper. On the other hand, the NO_x emitted during combustion depends on fuel composition, operation temperature and the project of the burners and the combustion chamber. Therefore, the "toxicity in internal combustion engines" section of this paper presents the emission factors for different analyzed fuels always considering ICE technologies.

4.1. Diesel

In Brazil, diesel fuel consumption is attributed to the transport sector, which represents 80% in the country energy matrix. From this total, 94% are destined to the road transport system. The Brazilian oil diesel, compared with the American and European, presents a high sulphur level. Since January 1998, the Brazilian diesel fuel has a maximum 0.5% of sulphur content [11]. The main pollutants when diesel fuel is used are: carbon dioxide, sulphur oxides and particulate material.

The traditional chemical formula for the petroleum diesel is $C_{12}H_{26}$ and its density is 0.948 ton/m^3 [12]. The combustion reaction for normalized air excess α follows:

$$1C_{12}H_{26} + 18.5\alpha O_2 + 69.56\alpha N_2 \rightarrow 12CO_2 + 13H_2O + 69.56\alpha N_2 + 18.5(\alpha - 1)O_2 \quad (4)$$

The stoichiometric *A*/*F* ratio for this reaction is 14.93. Adopting diesel burning with 100% air excess, after the stoichiometric balance, a percentage in mass of each compound resulting from this reaction is: 10.058% CO_2, 4.458% H_2O, 74.206% N_2, and 11.278% O_2 (Table 2). On the other hand, from its combustion reaction, the result is: 528 g of CO_2 for 170 g of diesel oil. Taking into account the density of the diesel fuel, the following is obtained: 528 ton CO_2 per 196.76 m^3 diesel, i.e., 2.683 ton CO_2 per m^3 diesel [13].

Applying the percentage in mass of each compound, it is possible to compose an equation for the specific heat (Cp) of the exhaust gases, in the case of diesel combustion [14]. Fig. 1 shows the values in function of the temperature.

$$Cp_D = 1.0039562 + \frac{3.39987 \cdot T}{10^5} + \frac{3.02996 \cdot T^2}{10^7} - \frac{1.3168 \cdot T^3}{10^{10}} \quad (5)$$

4.2. Gasoline

Gasoline is a fuel constituted basically of hydrocarbons and a small portion of oxygenized compounds. These hydrocarbons are, in general, less heavy fuels than those that compose diesel fuel, because they are formed by molecules of small carbonic chains (normally has 4–12 carbon atoms). Beyond the hydrocarbons and the oxygenized compounds, gasoline contains sulphur, nitrogen and metallic compounds, all these with low concentrations [11].

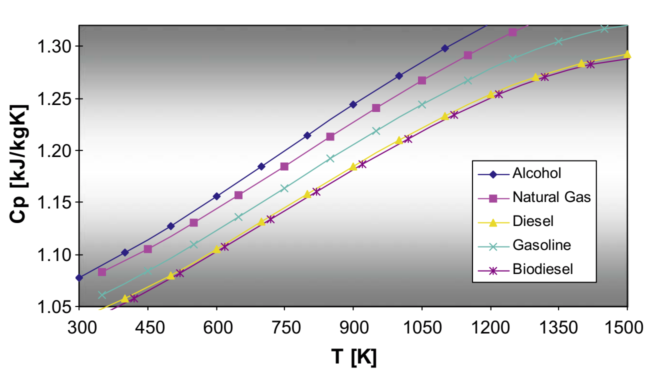

Fig. 1. Specific heat in constant pressure as a function of the temperature for the several fuels.

Blending of alcohol in gasoline is obligatory by Brazilian federal law. Currently, the Resolution No. 35 ANP (Petroleum National Agency), of February 2006, is in vigor, which determines that, from March 2006, the percentage of anhydrous alcohol blended in gasoline should not exceed 20%. This resolution applies for all gasoline types (common gasoline, *supra* gasoline, podium gasoline and premium gasoline).

The chemical formula of gasoline is C_8H_{18} (octane) and its density is 0.75 ton/m^3 [15]. The combustion reaction for normalized air excess α follows:

$$C_8H_{18} + 12.5\alpha O_2 + 47\alpha N_2 \rightarrow 8CO_2 + 9H_2O + 47\alpha N_2 + 12.5(\alpha - 1)O_2 \quad (6)$$

The stoichiometric *A*/*F* ratio for this reaction is 15.14. Considering gasoline burning with 30% of air excess, the percentages in mass of each compound resulting from the reaction is: 15.012% CO_2, 6.909% H_2O, 72.961% N_2 and 5.118% O_2. See Table 2 for details. On the other hand, the CO_2 emission for this fuel is 352 g of CO_2 for 114 g of gasoline. Taking into account the gasoline density, the result is: 352 ton of CO_2 for 152 m^3 of gasoline, which means: 2.316 ton of CO_2 by m^3 of gasoline [13].

Applying the percentage of each component mass the compound gasoline Cp equation is obtained, the Fig. 1, shows the values in function of the temperature [14].

$$Cp_{Gasoline} = 1.01104 + \frac{8.27999 \cdot T}{10^5} + \frac{2.73692 \cdot T^2}{10^7} - \frac{1.22778 \cdot T^3}{10^{10}} \quad (7)$$

Anhydrous ethanol is miscible in gasoline, which allows its use as a blend in automobiles, reducing gasoline consumption and discarding the use of specific antiknock agents. The percentage of anhydrous ethanol in gasoline has varied along the years between 20% and 25% in volumetric basis [16]. The chemical formula for ethanol is C_2H_5OH and its density is 0.79 t/m^3 [17]. The emission of CO_2 for this fuel is: 88 g CO_2 by 46 g alcohol; in consequence: 1.511 ton of CO_2 by m^3 of alcohol (see the reaction below).

$$1C_2H_5OH + 3\alpha O_2 + 11.28\alpha N_2 \rightarrow 2CO_2 + 3H_2O + 11.28\alpha N_2 + 3(\alpha - 1)O_2 \quad (8)$$

The stoichiometric *A*/*F* ratio for this reaction is 8.95. Considering 30% of air excess during burning, the percentages in mass of each compound resulting from this reaction are: 15.136% CO_2, 9.288% H_2O, 70.622% N_2 and 4.954% O_2 (see Table 2). Similar to gasoline, the equation for the Cp of the exhaust gases in the case of the alcohol combustion is considered. Eq. (9) shows the formula for Cp of ethanol as function of temperature [13].

$$Cp_{Alcohol} = 1.030048 + \frac{8.46416 \cdot T}{10^5} + \frac{2.81145 \cdot T^2}{10^7} - \frac{1.24471 \cdot T^3}{10^{10}} \quad (9)$$

4.3. Biodiesel

Chemically, biodiesel is composed of monoalkyl esters of long chains and fatty acids derived from renewable feed stock like vegetable oils and animal fats. It is produced by transesterification, in which oil or fat is reacted with a monohydric alcohol in presence of a catalyst. Biodiesel is used in compression ignition engines (diesel engines) or heating boilers. The biodiesel fuel has in general, the same or similar properties of the conventional diesel fuel and can be blended in any percentage with diesel fuel.

Biodiesel presents a slightly lower heating value (LHV) in comparison with the diesel fuel (117 Btu/gal, instead of 131 Btu/gal). Its kinematic viscosity, in general, varies between 1.9 and 6 cSt; this parameter does not differ much from the values corresponding to diesel fuel (1.3 and 4.1 cSt). Its density is approximately 0.878 ton/m^3 at 15 °C and its flash point is above 150 °C, which is higher than the value for diesel fuel, whose flash point varies between 60 and 80 °C. The flash point makes biodiesel safer to manipulate and to transport [18]. Biodiesel has a Cetane Number slightly higher than that for diesel fuel. It has a high lubricating power, which protects the engine. When added to regular diesel fuel, in amounts of 1–2%, it can convert fuels with poor lubricating properties, such as modern ultra-low-sulfur diesel fuel, into an acceptable fuel [19].

Biodiesel shows a wide variety of advantages on its fossil origin partner (diesel fuel). Nowadays, biodiesel is growing as a serious competitor in the energy market, which also takes into account the ecological benefits that its use represents. The average molecular weight of soybean oil methyl ester (biodiesel) is 292.2 g/gmol. This was calculated using the average fatty acid distribution for soybean methyl esters presented in Table 3. This table also shows the molecular weight and chemical formula for each of the component esters; each component was designated by a different character. From the stoichiometric combustion reaction with air, the emission rates of CO_2 are: 282.45 g of CO_2 by 100 g biodiesel, Eq. (10). Taking into account the fuel density, the following is obtained: 282.45 ton CO_2 per 113.88 m^3 of biodiesel, i.e., 2.48 ton CO_2 per m^3 soybean oil methyl esters (biodiesel) [13] (see Table 3 for A to E):

$$0.04437A + 0.01675B + 0.08432C + 0.1765D + 0.02052E + 9.037\alpha O_2 + 33.979\alpha N_2 \rightarrow 6.419CO_2 + 5.92H_2O + 33.979\alpha N_2 + 9.037(\alpha - 1)O_2 \quad (10)$$

Again, considering combustion with 100% air excess, the percentages in mass of each compound resulting from this reaction is: 10.943% CO_2, 4.13% H_2O, 73.72% N_2 and 11.20% O_2 (see Table 2). As in the previous cases, it is possible to obtain an equation for the Cp of the biodiesel exhaust gases. Fig. 1 presents the values of Cp as functions of temperature.

$$Cp_{Biodiesel} = 0.996432 + \frac{4.81565 \cdot T}{10^5} + \frac{2.89509 \cdot T^2}{10^7} - \frac{1.27827 \cdot T^3}{10^{10}} \quad (11)$$

4.4. Natural gas

According to COMGAS (Gas Supplying Company for the State of São Paulo, Brazil), the natural gas volumetric average composition is: CH_4 (methane) 89.3%; C_2H_6 (ethane) 8%; C_3H_8 (propane) 0.8%; C_4H_{10} and C_5H_{12} (butane and pentane) 0.1%; CO_2 (carbon dioxide) 0.5% and N_2 (nitrogen) 1.3%. With this composition, its molecular mass is 17.689 g gmol^{-1} and, consequently, its density is 789.68 kg/Nm^3. The following equation for normalized excess of air is utilized;

$$0.893CH_4 + 0.08C_2H_6 + 0.008C_3H_8 + 0.0005C_4H_{10} + 0.0005C_5H_{12} + 0.005CO_2 + 0.013N_2 + 2.118\alpha O_2 + 7.965\alpha N_2 \rightarrow 1.087CO_2 + 2.064H_2O + 7.965\alpha N_2 + 2.118(\alpha - 1)O_2 \quad (12)$$

The stoichiometric A/F ratio for this reaction is 16.44. Again, considering combustion with 40% of air excess, the percentages in mass of each compound resulting from this reaction are: 11.272% CO_2, 8.756% H_2O, 73.583% N_2 and 6.389% O_2 (see Table 2) [13]. The equation for Cp of natural gas is:

$$Cp_{Natural\ Gas} = 1.04435 + \frac{2.84032 \cdot T}{10^5} + \frac{3.2708 \cdot T^2}{10^7} - \frac{1.37905 \cdot T^3}{10^{10}}. \quad (13)$$

This is also plotted in Fig. 1.

5. The case of carbon in the biodiesel

Biomass-derived fuels decrease the net atmospheric carbon in two ways: first, they participate in the relatively rapid biological cycling of carbon to the atmosphere (via engine tailpipe emissions) and from the atmosphere (via photosynthesis). Second, they substitute fossil fuels. Fossil fuel combustion releases carbon that took millions of years to be removed from the atmosphere. Combustion of biomass fuels participates in a process that allows CO_2 to be rapidly recycled to fuel [20]. The main target for the use of bio-fuels is to decrease the emissions of gaseous pollutants to the atmosphere, mainly CO_2 emissions, with the purpose of reaching the targets of the Kyoto Protocol. As already indicated, the use of biodiesel takes with itself a global emission decrease.

A 1998 biodiesel life cycle study [20], jointly sponsored by the US Department of Energy and the US Department of Agriculture, concluded that biodiesel decreases the net CO_2 emissions by 78.45% compared to mineral diesel. This is due to the biodiesel closed carbon cycle. Therefore, considering this aspect, in the case of the use of B100 (biodiesel pure form), the result is: 0.578 ton CO_2 per m^3 with biodiesel.

6. Toxicity in internal combustion engines

The main toxic compounds in the exhaust gases of the internal combustion engines are carbon monoxide and nitrogen oxides. Carbon monoxide appears in the exhaustion gases as result of fuel incomplete combustion; the reason is insufficient oxygen in the combustion chamber or fuel particles that are not burned properly. Table 4 shows the main emissions of an internal combustion engine.

The substances that compose the exhaust gases can be classified in several groups. Nitrogen, oxygen, hydrogen, steam and carbon dioxide belong to not toxic group substances. The toxic group of substances includes carbon monoxide (CO), nitrogen oxides

Table 3
Typical soybean oil methyl ester [25].

Fatty acid	Weight (%)	Mol. Wt. (g)	Formula
Palmitic (A)	12	270.46	$C_{15}H_{31}CO_2CH_3$
Stearic (B)	5	298.52	$C_{17}H_{35}CO_2CH_3$
Oleic (C)	25	296.5	$C_{17}H_{33}CO_2CH_3$
Linoleic (D)	52	294.48	$CH_3(CH_2)_4CH{=}CHCH_2CH{=}CH(CH_2)7CO_2CH_3$
Linolenic (E)	6	292.46	$CH_3(CH_2CH{=}CH)_3(CH_2)7CO_2CH_3$

Table 4
Exhaust gases in internal combustion engines (volume percentage) [1].

Components	Maximum content in volume (%)		Observation
	Gasoline	Diesel	
Nitrogen	74–7	76–78	Non toxic
Oxygen	0.3–0.8	2.0–18.0	Non toxic
Steam	3.0–5.5	0.5–4.0	Non toxic
Carbon dioxide	5.0–12.0	1.0–10.0	Non toxic
Carbon monoxide	0.1–10.0	0.01–0.5	Toxic
Nitrogen oxide	0.1–0.5	0.001–0.4	Toxic
Hydrocarbons	0.2–3.0	0.009–0.5	Toxic
Aldehyde	0–0.2	0.001–0.009	Toxic
Sulphur dioxide	0–0.002	0–0.03	Toxic
Soot (g/m^3)	0–0.04	0.01–1.1	Toxic

(NO_x), hydrocarbons (C_xH_y), aldehydes (R_xCHO), soot, sulphur dioxides (SO_2), sulphydric acid and solid particles. The polyaromatic hydrocarbons (PAH) are carcinogenic substance and form a special group [21].

A small vehicle releases to the atmosphere in average between 0.6 to 1.7 kg/h of CO; a truck releases between 1.5 and 2.8 kg/h CO. In general, when 1 kg of diesel fuel is burned, it releases between 80 and 100 g toxic compounds, specifically: 20–30 g of CO, 20–40 g of NO_x, 4 to 10 g of HC (hydrocarbons), 10–30 g of SO_x, 0.8–1 g of aldehydes, 3–5 g of soot, etc. When 1 kg of gasoline is burned, it releases between 300 and 310 toxic compounds, specifically: 225 g of CO, 55 g of NO_x, 20 g of HC, 1.5–2 g of SO_x, 0.8–1 g of aldehydes, 1–1.5 g of soot [1]. PM emissions of diesel fuel for automotive vehicles are 13.2 kg/m^3 [22]; in the case of gasoline for automotives vehicles, the PM emission is 1.44 kg/m^3. On the other hand, an internal combustion engine burning natural gas, without any emissions control equipment in the tailpipe (i.e., catalyst), releases to the atmosphere: 13.61 g/MWh (1.35×10^{-5} kg/Nm^3) of PM-10; 0.26 g/GJ (9.58×10^{-7} kg/Nm^3) of SO_2 and 94.58 g/GJ (3.48×10^{-4} kg/Nm^3) of NO_x [23].

7. The biodiesel case

The use of bio-fuels in ignition compression engines can play a vital role in helping the developed and developing countries to reduce the environmental impact of fossil fuels. The main target for the use of bio-fuels is to decrease the emissions of gaseous pollutants to the atmosphere, mainly CO_2 emissions, with the purpose of reaching the targets of the Kyoto Protocol. As already indicated, the use of biodiesel takes with itself an emission net decrease. Fig. 2 shows the emissions of the main polluting agents. In the case of biodiesel combustion, the emissions are very low (with exception of NO_x).

The 100% reduction in the sulphur dioxide emissions is reasonable, because of its vegetal origin (vegetal oils and animal fats) that does not contain sulphur. The carbon monoxide emissions in the biodiesel combustion for engines diesel are 40–50% lower than conventional diesel fuel; this is consequence mainly by the presence of oxygen in the chemical formula of methyl esters or ethyl ester (biodiesel), leading to a more complete combustion. The PM emissions will reduce between 35% and 45% in comparison with diesel fuel [24]. A reduction of hydrocarbon emissions is produced due to a more complete combustion; the carbon–hydrogen and oxygen chains of esters generate CO_2 and H_2O in a complete process, making a difference to the diesel fuel [21].

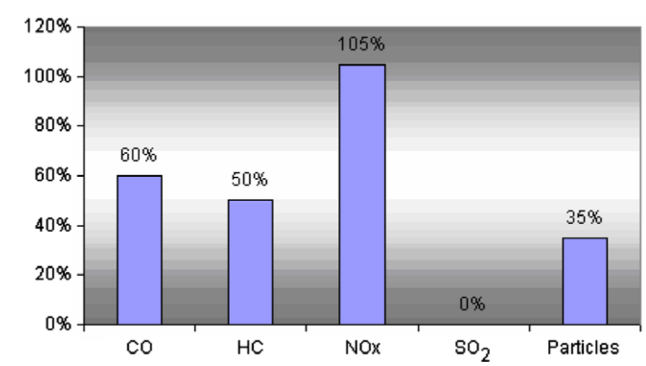

Fig. 2. Pollutants emissions of the biodiesel combustion in an internal combustion engine. The 100% is considered the emission level of the diesel engine [24].

The CO_2 case is different in respect other polluting agents. The emissions generated by biodiesel during the combustion in engines or boilers are "recyclable" through photosynthesis; combustion of bio-fuels participates in a process that allows CO_2 to be rapidly recycled to fuel [25,26].

The NO_x emissions increase in 5%. The increment is originated by the temperature increase in the tailpipe engine, which occurs due to reduction of the delay ignition, and, as consequence, to the injection point advance. All these parameters and the higher amounts of oxygen, makes the possible NO_x emissions to increase [27].

8. Ecological efficiency calculation

Table 5 shows a comparison between the fuels analyzed: natural gas, gasoline, diesel and biodiesel in internal combustion engines with reference to his emissions. In Fig. 3 are shown the ecological efficient values for the four fuels analyzed: diesel, gasoline, biodiesel (B100 and B20), and, finally, Fig. 4 shows the ecological efficient values in function of internal combustion engines efficiency.

9. Conclusions

This work shows that it is possible to evaluate the environmental impact by internal combustion engines using the ecological efficiency parameters; therefore, the following can be concluded.

The use of pure biodiesel (B100) or its mixture with diesel (B20) in internal combustion engines, especially in compression ignition engine, represents an excellent option on the ecological point of view.

The CO_2 emissions, according the fuel type in ton of CO_2 for m^3, were calculated. It is observed that the fuel with less CO_2 emissions to the atmosphere is natural gas and the one that it releases most is diesel fuel. Biodiesel presents a similar situation in respect to diesel fuel. In fact, biodiesel emits larger quantities of CO_2 than conventional fuel, but as most of this is from renewable carbon stocks. This fraction is not counted as greenhouse gas emission from the fuel; on the other hand, biodiesel has more oxygen molecules in comparison to diesel fuel; therefore, the combustion process is more complete and, as consequence, a reduction in the CO emissions is possible.

The carbon released by petroleum diesel was fixed from the atmosphere during the formative years of the earth, whereas the

Table 5
Comparison of results of pollutant emissions between the fuels analyzed in internal combustion engines.

Pollutant emission kg/kg of fuel	Nat. gas	Diesel	Gasoline *	Biodiesel B20	Biodiesel B100	Diesel/B100
CO_{2e}	2.727	8.529	5.891	7.502	3.423	2.5
PM	1.71×10^{-5}	15.27×10^{-3}	1.920×10^{-3}	14.21×10^{-3}	9.931×10^{-3}	1.5
NO_x	4.412×10^{-4}	4×10^{-2}	5.5×10^{-2}	4.04×10^{-2}	4.2×10^{-2}	0.9
SO_2	1.213×10^{-6}	3×10^{-2}	0.2×10^{-2}	2.4×10^{-2}	–	–
CO_2	2.704	3.106	2.853	2.61	0.658	4.7
Total (kg/kg of fuel)	2.7042	3.161	2.912	2.689	0.71	4.4
Ecological efficiency (%)	91.95	77.34	82.52	78,94	87.58	

* Gasoline with 20% of alcohol.

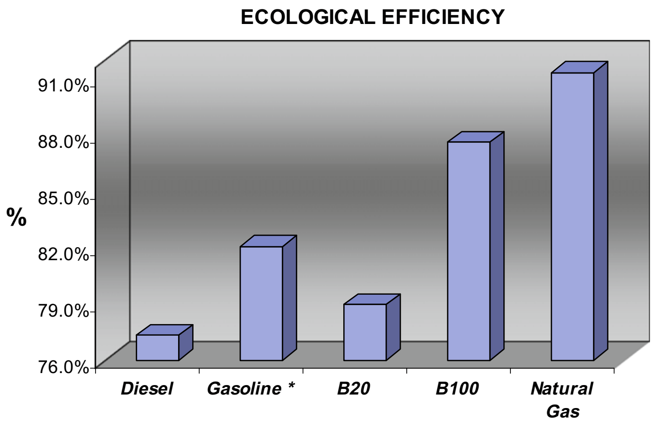

Fig. 3. Diesel, gasoline, biodiesel (B20 and B100) and natural gas ecological efficiency * gasoline with 20% anhydrous alcohol.

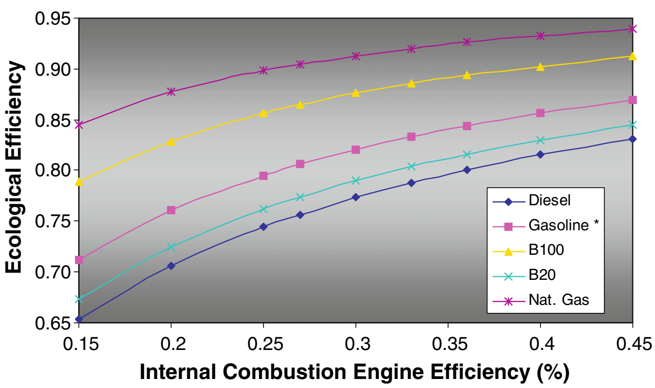

Fig. 4. Ecological efficiency variation in function of internal combustion engines efficiency. Gasoline with 20% anhydrous alcohol.

carbon released by biodiesel gets continuously fixed by plants and may be recycled by the next generation crops. Therefore, the main advantage of the biodiesel is that CO_2 emissions can be considered as recyclable by the growing plants. Then, the emission levels using this kind of bio-fuel are 78.45% lower in comparison with the diesel fuel. The calculated parameter is 0.578 ton of CO_2/m^3 of biodiesel (B100).

The emissions for internal combustion engines using pure biodiesel (B100) are: 0.658 kg/kg of fuel for CO_2, 0.042 kg/kg of fuel for NO_x and 0.009931 kg/kg of fuel of particulate material (PM). In the case to use 20% of biodiesel mixed with 80% diesel (B20), the emission levels are: 2.61 kg/kg of fuel for CO_2, 0.024 kg/kg of fuel for SO_2, 0.0404 kg/ kg of fuel for NO_x and 0.01421 kg/kg of fuel of particulate material (PM). The total emissions for diesel in comparison with the biodiesel (B100) are 4.4 times higher, based in kg/kg of fuel relation. The ecological efficiencies, for the analyzed fuels, natural gas, gasoline, diesel, biodiesel B100 and biodiesel B20 are, respectively, 91.95%, 82.52%, 77.34%, 87.58% and 78.94%. This study shows that the use of biodiesel as alternative fuel, from an ecological point of view, is better than the use of diesel fuel, presenting higher values of ecological efficiency.

References

[1] N. Patrakhaltsev, V. Gorbunov, O. Kamychnikov, Toxicidad en Motores de Combustión Interna (Toxicity in internal combustion engines), Universidad Rusa de la Amistad de los Pueblos, Moscu–Rusia, 1994 (in Spanish).

[2] M. Cardu, M. Baica, Regarding a global methodology to estimative the energy ecologic efficiency of thermopower plants, Energy Conversion and Management 40 (1999) 71–87.

[3] K.R. Salomon, Avaliação quantitativa do impacto ambiental das emissões gasosas e do uso da água de resfriamento em instalações de geração termelétrica (Quantitative evaluation of the gaseous emission environmental impact and of the cooling water use in thermoelectricity generation installations), Thesis (Master's degree) EFEI – Itajubá, Brazil, 2003 (in Portuguese).

[4] M. Cardu, M. Baica, Regarding a new variant methodology to estimative globally the ecologic impact of thermopowers plants, Energy Conversion and Management 40 (1999) 1569–1575.

[5] M. Cardu, M. Baica, A seismic vision regarding a methodology to estimative globally the energy – ecologic efficiency of thermopower plants, Energy Conversion and Management 42 (2001) 1317–1325.

[6] I.A.C. Villela, J.L. Silveira, Ecological efficiency in thermoelectrical power plants, Applied Thermal Engineering 27 (2007) 840–847.

[7] J.B. Heywood, Internal Combustion Engine Fundamentals, McGraw-Hill, New York, 1988.

[8] Collmus, Freiberger, Gasoline consumption of a highly throttled multi-cylindered engine, Thesis MIT library, June 1945.

[9] Y. Goto, K. Narusawa, Combustion stabilization of a spark ignition natural gas engine, JSAE Review 17 (1996) 251–258.

[10] C.F. Taylor, The Internal-Combustion Engine in Theory and Practice: Combustion, Fuels, Materials, Design, Ed. MIT, p. 795, 1985, ISBN 0262700271, 9780262700276.

[11] Brazilian Petrol S/A – PETROBRAS. <http://www2.petrobras.com.br/>, 2007 (accessed 01.08.07).

[12] P.T. Lacava, Investigação Experimental do Enriquecimento do Ar na Incineração de Resíduos Aquosos (Experimental investigation of air enrichment in the liquid waste incineration) Doctoral Thesis, Instituto Tecnológico de Aeronáutica (ITA), SP, Brazil, 2000 (in Portuguese).

[13] C.R. Coronado, J.A. Carvalho, J.L. Silveira, Biodiesel CO_2 Emissions a Comparison with the Main Fuels in the Brazilian Market According to the National Vehicles Fleets in the Last Four Years, Mechanical Engineering Brazilian Congress, COBEM, Brasilia, 2007.

[14] R.F. Boehm, Design Analysis of Thermal System, John Wiley and Sons, New York, 1987, ISBN: 0-471-83204-9.

[15] R.E. Perry, C.H. Chilton (Eds.), Chemical Engineers' Handbook, McGraw-Hill Book Company., Berlin, 1973.

[16] J.A. Carvalho, M.Q. McQuay, Princípios de Combustão Aplicada (Principles of Applied Combustion), UFSCP Ed, São Paulo – Brasil, 2007 (in Portuguese).

[17] V.H. Russomano, Introdução à Administração de Energia na Indústria (Introduction to Administration of Energy in Industry), São Paulo University Ed, SP – Brazil, 1987.

[18] Biodiesel handling and use guidelines, Energy Efficiency and Renewable Energy, second edition, US Department of Energy, March 2006.

[19] J. Van Gerpen, Biodiesel processing and production, Fuel Processing Technology 86 (2005) 1097–1107.

[20] J. Sheehan, V. Camobreco, J. Duffield, M. Graboski, H. Shapoiri, An Overview of Biodiesel and Petroleum Diesel Life Cycles, National Renewable Energy Laboratory, US Department of Energy, 1998.

[21] J.M.S. Lizarraga, Cogeneracion - Aspectos termodinámicos, tecnológicos y económicos (Cogeneration – Thermodynamics, Technological and Economics Aspects), Edit. Universidad del Pais Vasco, Bilbao - España, 1994, ISBN: 84-7585-571-7 (in Spanish).

[22] J.A. Carvalho, P.T. Laçava, Emissões em processos de combustão (Emissions in Combustion Process) Ed. Unesp, SP, Brasil, 2003, ISBN: 85-7139-484-9 (in Portuguese).

[23] F. Weston, N.L. Seidman, C. James, Model Regulations for the Output of Specified Air Emissions from Smaller – Scale Electric Generation Resources, The Regulatory Assistance Project, 2001.

[24] French Institute of Petroleum. <http://www.ifp-school.com/>, 2007 (accessed 01.08.07).

[25] National Biodiesel Foundation, National Biodiesel Board, http://www.biodiesel.org/aboutnbb/foundation, 2007.

[26] B.K. Barnwal, M.P. Sharma, Prospects of biodiesel production from vegetable oils in India, Renewable and Sustainable Energy Reviews 9 (2005) 363–378.

[27] Knothe Gerhard, Dependence of biodiesel fuel properties on the structure of fatty acid alkyl esters, Fuel Processing Technology 86 (2005) 1059–1070.