

Comparative Study between Diesel Fuel and Hydrated Ethanol in Direct Burning

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Abstract

This paper presents a theoretical and experimental study about the substitution of diesel fuel used in small combustion units for hydrated ethyl alcohol. The study is focused on the physical chemical properties of the diesel fuel and hydrated ethyl alcohol, thermodynamics of combustion, atomization, and pollutants formation. The pollutants investigated were carbon monoxide (CO), unburned hydrocarbons (UHC), nitrogen oxides (NO_x) and carbon dioxide (CO₂). The theoretical and experimental results show that the same burner used for diesel fuel can be used for hydrated ethanol, with improvement in atomization and combustion efficiency, and reduction of pollutants emission. It is demonstrated that hydrated ethanol is a potential substitute to the diesel fuel in industrial direct burning.

Introduction

Renewable energy is an important issue to many countries and governments, since it provides a means of reducing carbon dioxide emissions and contributes to meet the Kyoto Protocol objectives [1,2]. The use of hydrated ethyl alcohol fuel (AEHC) for direct burning in industries has been discouraged in Brazil since the start of the PROALCOOL program in 1975 [3], mainly due to the fuel higher relative cost compared to the most used fuels. Over the last decades, however, the difference of prices between petroleum derived fuels and ethyl alcohol has decreased, and this happened mainly when diesel fuel is considered. Such difference can be even further decreased if government policies for price adjustment are implemented, such as: regulation norms for the market fuel, investments in research and incentive to production. The PROALCOOL was designed to provide Brazil an installed production capacity of 16 billion liters a year; currently, 10.4 billion liters a year are produced, which means 65% of the initially projected sugar cane industry capacity. Moreover, the sugar cane plantation areas constitute a small portion of the country cultivatable lands. The area with sugar cane represented, in 2001, 10.8% of the cultivated area in Brazil, which is equivalent to less than 1% of the total cultivatable lands [4].

The world crisis in the 70's evidenced the dependence and vulnerability of countries in regard to the supply of petroleum. In an attempt to solve the problem, some countries concentrated attention in the development of alternative fuel, with emphasis in the alcohols. First, efforts were mainly focused in the substitution of the gasoline utilized in Otto cycle engines. The use of alcohol in diesel engines, although in preliminary works, was also investigated. The United States and Brazil were the countries that attained higher advances in such research. A mixture of 10% of anhydrous ethanol and gasoline was and continues being commercialized in the Mid East states of the United States [5].

The PROALCOOL is today the largest program for the use of bio-fuels. Since its start, engines that utilize 100% of hydrated ethanol were developed in the country; besides, the cars that run with gasoline, actually consume a mixture of 20 to 25% of anhydrous ethanol and gasoline [6]. On the other hand, the use of ethanol in diesel engines has begun in the 70's in South Africa and has continued in Germany and in the United States in the 80's [7].

Research on the use of alcohol in diesel engines has increased in the last decades. The following techniques have been investigated: fumigation, double injection, emulsions and micro-emulsions (or solutions). In fumigation, the ethanol is introduced in the engine via carburetion, vaporization or injection in the air flow [8]. In double injection, a separate injection system is utilized for each fuel [9]. Emulsions are mixtures between the two fuels, for which there are two liquid phases in equilibrium, where small droplets of ethanol are suspended in the diesel fuel [5]. In micro-emulsions, a solvent is used to form a homogeneous mixture between the two fuels [10].

Another application of alcohols currently under research is the production of bio-diesel from methanol and ethanol by means of the transesterification process. This technique consists in the reaction of oil with an alcohol to form esters and glycerol [11].

Little research was conducted in the use of alcohol in direct burning. Some works developed in the subject have shown promising results. Addition of methanol during the start up of a thermal power station in Spain has been reported [12]. Methanol and ethanol in fractions of 5, 10 and 15% were added to light oils, and a reduction of particulate material and unburned hydrocarbon emissions was observed. The decrease was proportional to the fraction of alcohol added. Ethanol was more effective than methanol in reducing the emissions.

Reference [12] also discusses results obtained in the United States during combustion of alcohol in boilers and gas turbines. The Vulcan Cincinnati Company conducted tests of combustion of methanol in 49 MW

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commercial boilers. NO_x emissions were 4 and 10 times lower than those obtained with natural gas and fuel oil, respectively. The General Electric Company conducted tests showing decrease of 40% in NO_x due to the lower gas temperatures. The Florida Power Corporation conducted test with methanol in an 18 MW gas turbine, and the NO_x emissions decreased 74% in comparison with the values obtained with light oil.

In Brazil, fuel oil is the most utilized fuel in industrial burners. Diesel fuel is used in lower scale, mainly in applications where a clean fuel is required, or in small units where fuel oil cannot be utilized because of the lack of steam to heat up the fuel to an adequate temperature for pumping and atomization. In Brazil, the prices of diesel fuel and ethanol compete with each other. Therefore, it is of interest to conduct a comparative study on the utilization of ethanol and diesel fuels in industrial burners, and this is the subject of the present article.

Discussion on Characteristics of Both Fuels

Physical Chemical Properties

The kinematic viscosity of diesel fuel at 37.8 °C is approximately twice of that of ethyl alcohol (2.46 and 1.1 mm²/s, respectively) [5]. The lower viscosity of AEHC produces a reduced droplet average diameter during atomization, creating the potential for better mixing between fuel and air and, in consequence, for the achievement of higher combustion efficiencies.

The lubrication in the burners that use diesel fuel can be carried out by the own fuel, and the pumps can be of the rotating type, with positive displacement. Due to its low viscosity, AEHC cannot be transported with such pumps, nor be used as lubricant. Therefore, it cannot be used directly without previous modifications of the pumping system and the burner lubrication process.

Volatility has great importance in the burning of a liquid fuel. Its increment increases the performance of combustion and decreases the emissions of CO, unburned hydrocarbons, and particles. On the other hand, a higher volatility means higher risks of losses by evaporation and fires. It also implies in low luminosity of the flame. The volatility of a fuel can be evaluated from the knowledge of its distillation interval, steam pressure and the flash point.

For the same temperature, the ethanol vapor pressure is higher than that for diesel; the difference increases as the temperature increases. Ethanol is then more volatile, which is in favor of a better combustion. At atmospheric pressure, ethanol evaporates at 78 °C, while the diesel fuel, due to being a mixture of hydrocarbons, evaporates in the interval 177 to 337 °C.

The flash point is the lowest temperature at which the fuel produces enough vapor to form a flammable mixture with air. This property is 13 °C for ethanol and 64 °C for diesel [13]. This means that ethanol can ignite before the diesel fuel; at room temperature, ethanol forms sooner a flammable mixture with air.

The flammability limit interval is larger than the ones for diesel and gasoline [13]. This means that ethanol can form flammable mixtures with air in a wider range of values, at the cost of higher losses to vapor and higher risks of fire.

Thermodynamic Calculations for the Fuels

Thermodynamic calculations for the fuels under study were performed for adiabatic flame temperatures and volume of combustion products. The ethanol was considered as 93° INPM (93 % ethanol, 7 % water, mass basis). The chemical formulas for diesel and dry ethanol were taken as CH_{1.81} and C₂H₅OH, respectively.

The calorific value for hydrated ethanol is approximately 60% of that for diesel fuel; however, the stoichiometric air/fuel mass ratio for ethanol is approximately 58% of that for diesel, which makes the amount of air required per unit of released energy 94.7% for ethanol in relation to diesel. It is also observed that the adiabatic flame temperatures for both fuels are nearly the same. For the same amount of energy liberated, the flow rates of product gases will be approximately the same for both fuels, implying that the residence times and turbulence levels inside the combustion chamber will be approximately the same. The fact that the flame temperature, the volume of gases, the residence time and the turbulence level are nearly the same for both fuels means that these parameters, by themselves, will not modify the emission values of each one when substitution of diesel by hydrated ethanol is conducted.

It is also observed from the table that the amount of CO₂ produced by diesel fuel is slightly higher (5.4%) of that produced by hydrated ethanol.

Atomization

In this item, a comparison of the average diameter of droplets generated in a Y-type atomizer is performed for diesel and hydrated ethanol. Y-type atomizers, whose scheme is presented in Figure 1, are commonly used to break liquid fuels into droplets in industrial applications. Two atomizers have been calculated (one for diesel fuel and the other for ethanol), following the procedure described by Lacava [14]. The mass flow rate assumed for diesel was 5 g/s. Considering that the calorific value for hydrated ethanol is 59% of that for diesel, the corresponding mass flow rate of ethanol to liberate the same power was 8.45 g/s. The predicted mass median diameter (MMD) was calculated for the four situations, using Wigg's equation [15]:

$$MMD = \frac{200v^{0.5}w^{0.1}(1+F/A)^{0.5}h^{0.1}\sigma^{0.2}}{\rho_{at}^{0.3}V}, \quad (1)$$

where the MMD is given in [μm], v is the kinematic viscosity of the fuel [cSt], F is the fuel mass flow rate [g/s], A is the mass flow rate of the atomization air [g/s], h is the radius of the mixture chamber [cm], σ is the fuel surface tension [dyne/cm], ρ_{at} is the density of

the atomization air [g/cm^3], and V is the relative velocity between air and fuel [m/s].

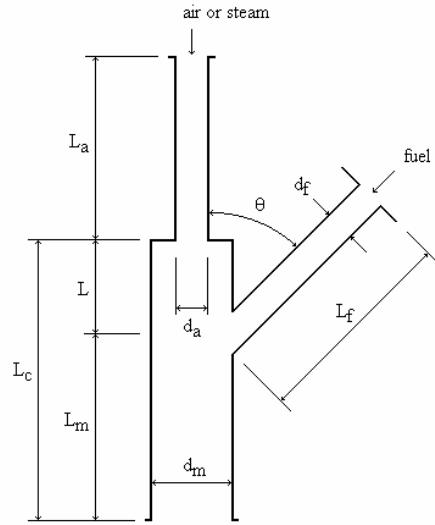


Figure 1 – Scheme of a Y-type atomizer.

The results are presented in Table 1. The fuel/atomization air ratio was increased from the recommended design value of 0.1, keeping the other parameters constant. The results are presented in Figure 2. It is observed that the mean mass diameters produced with ethanol are lower in all cases in comparison to those corresponding to diesel. The best choice regarding the mass median diameter is case 2 of ethanol, in which the same atomizer for diesel is used. This case also corresponds to the higher stagnation pressure.

Flame Characteristics and Soot Formation

Liquid fuels can burn as individual droplets or in group [16]. Diluted sprays of non volatile fuels or those with large droplets allow enough diffusion of air into their central region, so that the reacting mixture can occur within the flammability limits, forming flames around individual droplets. Given the broad variation of droplet sizes, speeds and directions, sprays under burning of individual droplets present irregularities in the reacting mixture, and rich and lean zones occur at the same time. Soot and larger particulate material are formed in the rich zones, giving the flame its characteristic yellow color. These zones can also be favorable to the formation of cyan-compounds, which react to form NO_x by the prompt mechanism [17].

In group combustion, flames are formed around clouds of droplets. In dense sprays of volatile fuels and in those with small droplets, the amount of fuel vapor can be so high that it prevents the entrance of necessary oxygen to form a flammable mixture in the spray central region. The flame is, then, formed in the peripheral region where enough oxygen is available. These flames are homogeneous and similar to the flames of a gaseous fuel. They do not form soot and have a blue characteristic color. Because it does not form particulate material, this type of flame radiates small amounts of

energy, and the temperatures are high, generating NO_x by the thermal mechanism.

Table 1 – Theoretical results obtained with four Y-type atomizers, for power output of 5 g/s of diesel fuel.

Parameter	Diesel	Alcohol case 1	Alcohol case 2
w: fuel mass flow rate [g/s]	5	8.45	8.45
A: atomization air mass flow rate [g/s]	0.5	0.845	0.845
d_a : diameter of the inlet duct [mm]	1.0	1.2	1.0
Ma: Mach number [non dimensional]	1	1	1
T_0 : atomization air stagnation temp. [K]	300	300	300
P_0 : atomization air stagnation press. [atm]	3	3	4.55
ν : fuel kinematic viscosity [cSt]	3.71	1.78	1.78
T: atomization air temperature [K]	250	250	250
P: atomization air pressure [atm]	1.58	1.58	2.40
ρ_{at} : air density [kg/m^3]	2.24	2.24	3.40
V: relative velocity, air and fuel [m/s]	317	317	317
MMD: mass median diameter [μm]	44.4	32.2	27.8

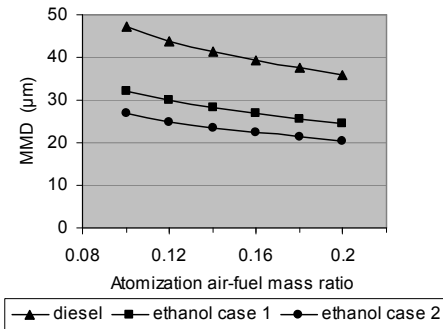


Figure 2 – Variation of the droplet mass median diameter with the fuel/atomization air ratio.

Due to the high volatility of ethanol, it atomizes into finer droplets in a more dense spray than diesel. Ethanol is, then, expected to burn as group combustion, which is confirmed experimentally in references that report a blue flame without soot and with low radiation intensity for the fuel [18,19]. Ref. [18] explicitly characterized the flame of ethanol as internal group combustion.

Diesel fuel possesses low volatility and it is, then, expected that it burns as individual droplets. Considerable amounts of soot have been reported in the burning of diesel fuel with pressure atomizers, which is

an indication of combustion as individual droplets [20-22].

Pollution Characteristics

Ethanol is an alternative to diesel fuel to reduce pollutants emission. Because it has oxygen in its molecule structure and water in its composition (7% in mass), it is a highly volatile fuel. Blends of ethanol or water in diesel fuel have been investigated [9, 23-25]. When ethanol is added to diesel, the main benefit is a reduction of soot, followed by a reduction of CO. Temperature, CO and NO_x emission rates decrease as the percentage of ethanol was increased for blends with diesel [23]. Suppes [9] analyzed the experimental results of different authors and concluded that an effective reduction of soot formation occurs when ethanol is added to diesel. However, he states that the same cannot be concluded for NO_x, because some researchers have reported reduction but others have reported the contrary. Xing-Cai et al. [24] and Lin and Wang [25] have shown reduction of soot and NO_x when using ethanol-water-diesel fuel blends.

Finally, because ethanol is a bio fuel, it does not emit CO₂ as a greenhouse gas.

Experimental Analysis

In this item a comparison based on experiment is performed for both fuels. Atomization is the most important step in the burning process of a liquid fuel; therefore, the formation of pollutants will be investigated under the influence of atomization parameters.

Figure 3 presents a scheme of the combustion chamber utilized in the tests. A Y-type atomizer and an axial swirler were installed in the bottom of the combustion chamber. The combustion gases were sampled at the exit of the chamber. The atomizer was designed for a nominal mass flow rate of 0.9 g/s of diesel fuel. Its dimensions are presented in Table 2. In the tests, the liberated power was held constant, at 21 kW, which corresponded to 0.5 g/s of diesel fuel and 0.845 g/s of ethanol. Both fuels were burned with an excess of air of 29% above the stoichiometric air flow rate. The air flow rate was measured with an orifice plate. The atomization air and the fuel flow rates were measured with rotameters. The swirl number was 0.57 for both situations.

The quantities of pollutants emitted in the diesel and ethanol burns were compared varying the atomization ratio. This was obtained keeping the fuel mass flow rate constant and increasing the atomization air mass flow rate. Rosemount gas analyzers were used to measure the component concentrations.

The error for the atomization ratio corresponds to the error of the fraction atomization air flow rate and the fuel flow rate. This was determined from [26]:

$$\frac{\sigma}{R_{AT}} = \sqrt{\left(\frac{\sigma_A}{A}\right)^2 + \left(\frac{\sigma_F}{F}\right)^2}, \quad (2)$$

where σ is the error of the atomization ratio, R_{AT} is the atomization ratio, σ_A is the error of the atomization air flow rate, σ_F is the error of the fuel flow rate, A is the mass flow rate of the atomization air [g/s], and F is the fuel mass flow rate [g/s]. The characteristics and errors associated with the rotameters are presented in Table 3.

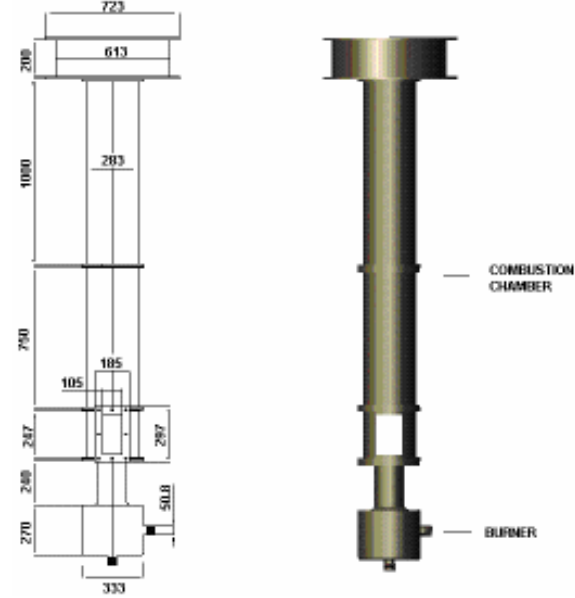


Figure 3 - Combustion chamber (dimensions: mm).

Table 2 – Dimensions of the Y-type atomizer.

Dimension	d _a	d _f	d _m	L	L _m	L _a	L _f
(mm)	0.4	0.4	0.6	0.3	3.0	1.2	3.4

Table 3 – Errors of rotameter measurements.

Fluid	Scale	Error (g/s)
	(g/s)	
Hydrated ethanol	0 – 1.2	0.012
Diesel fuel	0 – 0.8	0.08
Atomization air for ethanol combustion	0 – 0.47	0.0047
Atomization air for diesel combustion	0 – 0.32	0.0032

Figures 4 to 7 present the concentrations of CO₂, CO, UHC and NO_x, corrected to 3% O₂, for the burning of diesel fuel and ethanol. It can be observed that the concentrations of CO₂ are slightly higher for diesel fuel than for ethanol, as a consequence of the higher carbon content in the diesel fuel. The concentrations of CO and UHC are notably higher for diesel, except for the larger values of the atomization ratio. The most important difference in the test results occurs in the production of NO_x. For ethanol, the concentrations of NO_x are within 0 and 20 ppm; for diesel, the concentrations vary between 60 and 90 ppm.

It can also be observed that for both fuels the concentrations of CO and UHC decrease with an increase of the atomization ratio, and the contrary occurs with NO_x. This is an indication that the burning

process becomes more efficient as the atomization ratio increases.

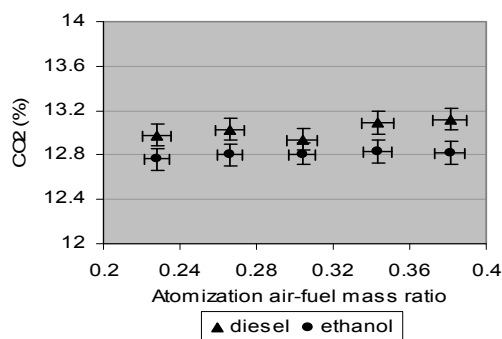


Figure 4 - Concentration of CO₂ (corrected to 3% O₂) as function of the atomization ratio; heat output of 21 kW.

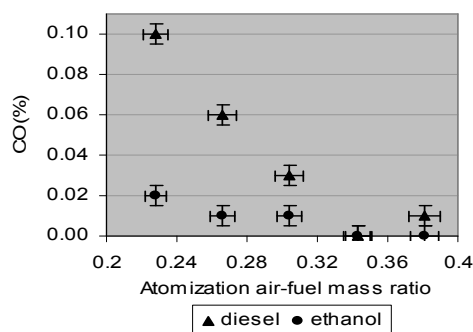


Figure 5 - Concentration of CO (corrected to 3% O₂) as function of the atomization ratio; heat output of 21 kW.

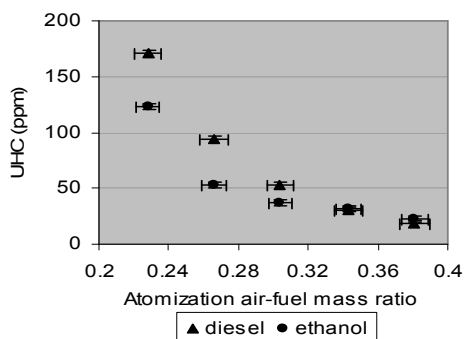


Figure 6 - Concentration of UHC (corrected to 3% O₂) as function of the atomization ratio; heat output of 21 kW.

Measurements of soot emission rates were not conducted. However, great amounts of soot were observed during combustion of diesel. In the alcohol combustion are not visualized soot emissions.

The lower rates of emitted pollutants in the combustion of ethanol can be linked to the high volatility of the fuel, which results in group type combustion of droplets. The presence of water in the composition of the hydrated ethanol also favors a decrease of pollutants emission. Water decreases the

flame temperature and, consequently, decreases the formation of thermal NO_x. According to Lenço [19], a technique used to control the emission of NO_x is the injection of 5 to 10% of water in the form of liquid or steam in the combustion zone. Water is also known as an agent that reduces formation of soot. Williams [27] states that the formation of soot in a spray can be minimized by the addition to the fuel of 5 to 15% of water in the form of an emulsion.

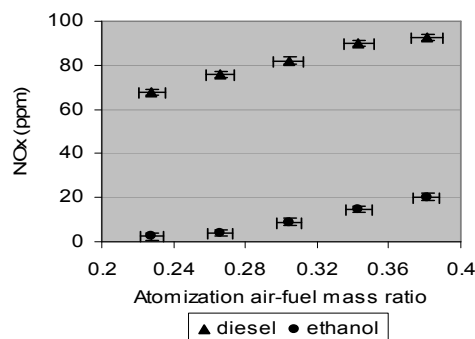


Figure 7 - Concentration of NO_x (corrected to 3% O₂) as function of the atomization ratio; heat output of 21 kW.

Conclusion

Hydrated ethanol is presented as a potential substitute to the diesel fuel in industrial direct burning. This is due to the following reasons:

- It is possible to use same diesel atomizer for ethanol, with a considerable improvement in the atomization and, therefore, in the combustion efficiency. It is important to observe that this substitution can only be achieved with an adjustment in the atomization air pressure.
- It is possible to use the same combustion chamber without change of the turbulence level and the gas residence time. This occurs because the temperature and the gas volume flow rate do not vary significantly from operation with either of the fuels at the same power output.
- A reduction in the emissions of CO, UHC, NO_x and soot was observed during the burning of hydrated ethanol. Since ethanol does not contain sulfur, SO₂ will not be release during its combustion. Diesel contributes to global warming differently than ethanol, because the culture of sugar cane absorbs CO₂ (i.e., ethanol is a bio fuel). A reduction of NO_x has been observed. The same has been also observed by other authors, although this cannot be expected to always occur.

To carry out a satisfactory substitution of diesel by hydrated ethanol, the following difficulties have to be taken care of:

- The lubrication of the fuel injection system has to be modified; ethanol does not present a high enough viscosity to allow its use as a lubricant.
- Losses by evaporation have to be prevented to avoid risk of fire, mainly in the storage reservoirs.
- The corrosive action of ethanol must be reduced,

either by inhibitors or by substitution of materials by others that are able to bear attack by ethanol.

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