Análisis experimental comparativo de la quema de etanol y diésel en un sistema de combustión común

Comparative experimental analysis of ethanol and diesel combustion in a common combustion system

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Abstract

This applied experimental study aimed to compare pollutant emissions and flame characteristics in the combustion of diesel and hydrated ethyl alcohol using the same combustion system, composed of a combustion chamber, a Y-Jet atomizer, and a swirler-type flame stabilizer. The research followed a quantitative approach and a comparative experimental design. The independent variable was the type of fuel, while thermal power output was kept constant at 21 kW. The response variables analyzed were emissions of CO, NOx, particulate matter, and flame characteristics. High-precision instruments—such as rotameters, type K thermocouples, and gas analyzers—were used under controlled conditions of atomization ratio, air pressure, and excess air coefficient. As a results, combustion of hydrated ethanol generated blue flames typical of group combustion, with significantly lower emissions of NOx, CO, and soot compared to diesel. Diesel exhibited droplet combustion, characterized by yellow flames, high radiation, and considerable soot production. Ethanol's high volatility, along with the presence of water and OH radicals, contributed to more complete combustion and lower pollutant levels. In conclusion, hydrated ethanol proved to be a technically feasible alternative to diesel in industrial burners, offering environmental advantages due to reduced pollutant emissions.

Its application requires only modification of the pumping system, owing to ethanol's lower viscosity and inadequate lubricity for diesel-type fuel pumps.

Keywords: energy biomass, chemical processes, chemical compounds.

Resumen

Este estudio experimental aplicado tuvo como objetivo comparar las emisiones de contaminantes y las características de la llama en la combustión de diésel y alcohol etílico hidratado utilizando el mismo sistema de combustión, compuesto por una cámara de combustión, un atomizador Y-Jet y un estabilizador de llama tipo remolino. La investigación siguió un enfoque cuantitativo y un diseño experimental comparativo. La variable independiente fue el tipo de combustible, mientras que la potencia térmica se mantuvo constante a 21 kW. Las variables de respuesta analizadas fueron las emisiones de CO, NOx, material particulado y las características de la llama. Se utilizaron instrumentos de alta precisión, como rotámetros, termopares tipo K y analizadores de gases, en condiciones controladas de relación de atomización, presión de aire y coeficiente de exceso de aire. Como resultado, la combustión de etanol hidratado generó llamas azules típicas de la combustión en grupo, con emisiones significativamente menores de NOx, CO y hollín en comparación con el diésel. El diésel exhibió una combustión de gotas, caracterizada por llamas amarillas, alta radiación y una producción considerable de hollín. La alta volatilidad del etanol, junto con la presencia de agua y radicales OH, contribuyó a una combustión más completa y a una reducción de los niveles de contaminantes. En conclusión, el etanol hidratado demostró ser una alternativa técnicamente viable al diésel en quemadores industriales, ofreciendo ventajas ambientales gracias a la reducción de emisiones contaminantes. Su aplicación solo requiere la modificación del sistema de bombeo, debido a la menor viscosidad del etanol y a su insuficiente lubricidad para las bombas de combustible diésel.

Palabras clave: biomasa energética, procesos químicos, compuestos químicos.

INTRODUCTION

Currently, climate change has become one of the greatest threats and challenges facing humanity (Pinto, 2019); in recent years it has been seen through news published in the press media how the effects of climate change are becoming increasingly important. Natural phenomena such as hurricanes, tornadoes, forest fires, floods, droughts and others are becoming more serious and more frequent. Climate change is mainly due to fossil fuels use as a source of energy, which emit greenhouse gases such as carbon dioxide and methane, which increase the planet's temperature. Biofuels from crops have become an important alternative to fossil fuels, including liquid biofuels such as ethanol, which together with carbon capture and storage technologies can help achieve negative carbon emissions (Köberle, 2019). This is because biomass absorbs CO2 from the atmosphere and assimilates it into its structure as carbon, the carbon is then integrated into the biofuel, when burned it produces CO2 which can be captured and stored in the subsoil (Grandis et al., 2024).

Ethanol is blended with gasoline in Otto engines at various percentages. In the United States, it is commonly used in blends containing 10%, 15%, and between 51% and 83% ethanol, as noted by the U.S. Department of Energy. In Brazil, a 27% ethanol blend is used (Barros, 2016). Additionally, Bioethanol is produced from energy crops. In the USA it is produced from corn, in Europe from sugar beet, in South America it is mainly produced from sugar cane, with Brazil as the main producer. Bioethanol has long been used as fuel in this country; it began to be used in 1975 with the creation of the national alcohol program, PROALCOOL, as a consequence of the first oil crisis in 1973. Since the creation of this program, Brazil has invested significant resources in infrastructure and research for the production and use of this biofuel, reducing its operating costs, making it competitive with other fuels and reducing greenhouse gas emissions by up to 80% (Walter et al., 2011)

Brazil continues to invest heavily in bioethanol research, with the aim of diversifying its application, such as in aeronautical gas turbines and industrial burners. This research article is framed within this vision and its main objective is to carry out an experimental comparison of pollutant emissions and flame characteristics of diesel and hydrated ethyl alcohol burning in the same combustion system composed by: combustion chamber, atomizer and flame stabilizer; in order to know the technical feasibility of replacing diesel used in industrial burners with hydrated bioethanol. This article is the continuation of another work published by Paz (2009) where a theoretical comparison is made in the same burning system. Both publications are the result of the PhD Thesis carried out by Paz (2009) at the Laboratory of the Faculty of Mechanical Engineering of Guaratinguetá and at the Combustion and Propulsion Laboratory of the National Institute of Space Research (INPE), in Brazil.

METHODOLOGY

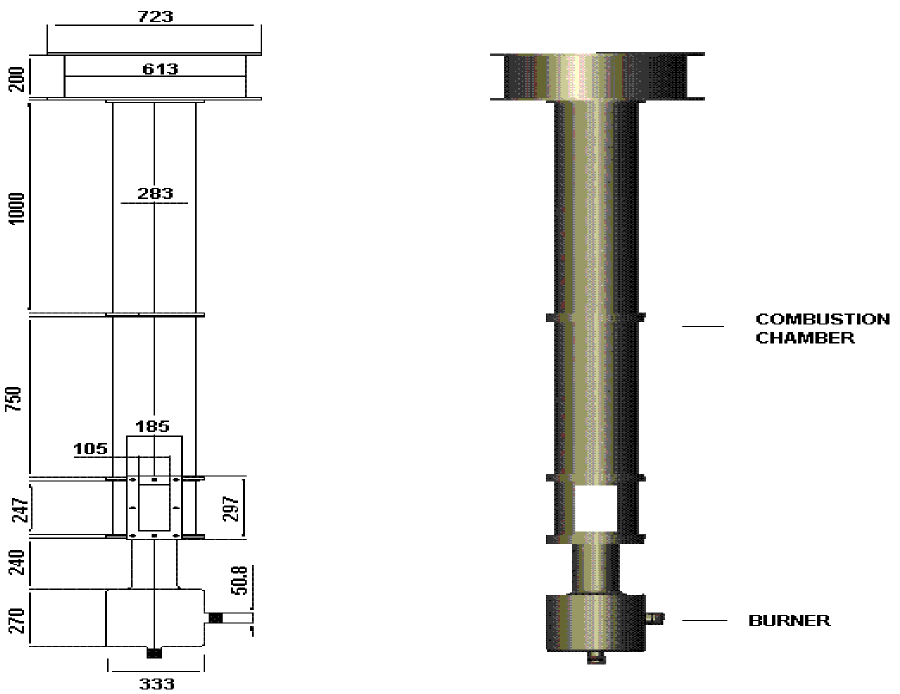
This study is classified as applied research, as it seeks to address a practical, real-world challenge: the technical and environmental assessment of replacing diesel with hydrated ethanol in industrial combustion systems. Instead of focusing on theoretical exploration, the research is directed toward enhancing combustion efficiency and minimizing pollutant emissions in industrial applications. Besides, this study adopts a comparative experimental design, involving the deliberate manipulation of the independent variable. Additionally, the research follows a quantitative approach, utilizing precise measurement instruments to collect numerical data. That’s why this methodological framework ensures objective analysis, reproducibility, and scientific rigor (Hernández Sampieri et al., 2014).

In this study, the combustion of diesel and hydrated ethyl alcohol in the same burning system and releasing the same thermal power was compared. The independent variable is the fuel used (diesel and ethyl alcohol). The response variables compared were the emission of pollutants (CO, UHC, NOx and particulate matter) and flame characteristics. The comparison was made under the effect of the following intervening factors: effect of atomization, flame stabilizer and excess air.

The tests were realized in a vertical combustion chamber with water jackets to cool the walls. Figure 1 is shown a diagram of the combustion chamber with its measures in mm. On the other side, the burner is installed under the combustion chamber. It is formed by a flame holder and an injector. The flame holder is a type axial swirler with variable blades; it is showed in Figure 2. The axial swirler was projected and constructed following the methodology presented by Muniz (1993). It has 8 variable angle blades, with 2 mm thickness, external diameter "de" of 157 mm and internal diameter "di" of 42 mm.

Figure 1

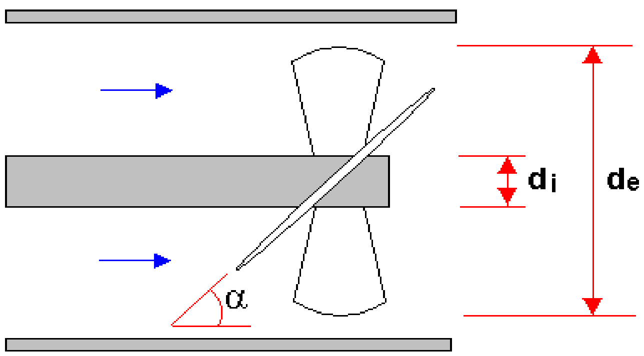
Combustion chamber



Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

Figure 2

Axial swirler flame holder



Note. Adapted from *Comparative study between diesel fuel and hydrated ethanol in direct burning*, by E. P. Paz, J. A. Carvalho Jr., L. R. Carrocci, E. V. Cortez, & M. A. Ferreira, 2009.

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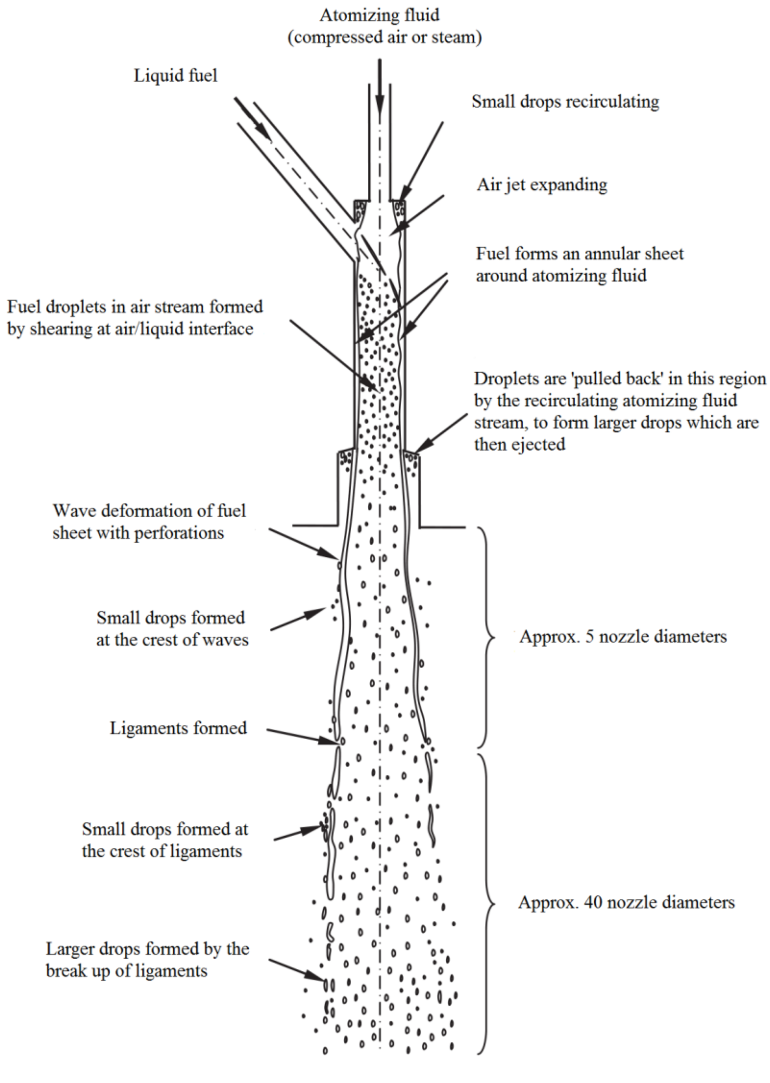
"Y" atomizer is a twin-fluid atomizer, widely used in oil boilers, industrial ovens, agricultural sprays, spray dryer and spray painting (Zhou et al., 2010). It is an air-assisted injector that uses a gas at high speed on the liquid fuel, the atomization process being influenced by injection pressure, liquid and gas properties and geometric configuration of the injector (Lacava et al., 2004; Song and Lee, 1996).

The physical atomization process on Y-type atomizer is shown in Figure 3 where the liquid fuel is injected into the mixing chamber at specific angle (Mullinger, 1974).

Figure 3

Liquid atomization on a Y-Jet type injector

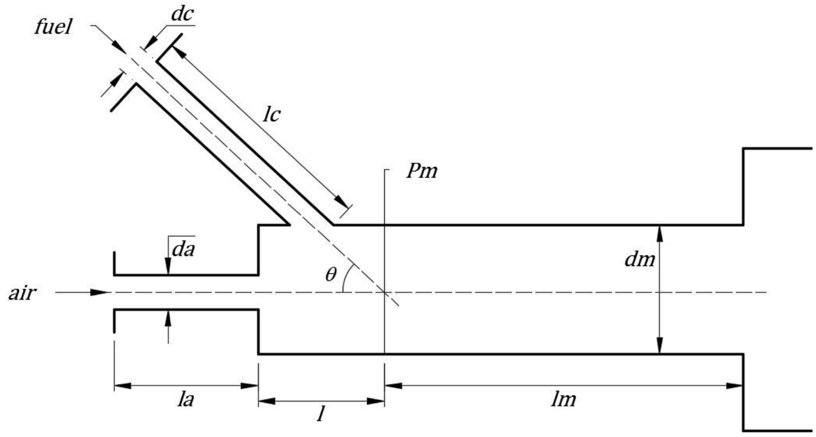


Note. Adapted from *The design and performance of internal mixing multijet twin fluid atomizers*, by P. Mullinger, 1974.

The injector is of the "Y-Jet" atomizer type and use compressed air for atomization. Its dimensions are showed in Figure 4. The atomizer was projected by applying the methodology presented by Lacava (2000). The diesel flow rate was 0.8 g/s, the atomization ratio was 0.1, and, the stagnation pressure and temperature were 300 kPa and 300 K, respectively. The atomizer dimensions are shown in the Table 1.

Figure 4

Y-Jet atomizer



Note. Adapted from *Experimental investigation of air enrichment in the incineration of aqueous waste* (in Portuguese) (Doctoral thesis, Instituto Tecnológico de Aeronáutica), by F. Lacava, 2000.

Table 1

Y-Jet atomizer dimensions

dimensions	***da***	***dc***	***dm***	***l***	***lm***	***la***	***lc***
(mm)	0.4	0.4	0.6	0.3	3.0	1.2	3.4

The combustion air flow was measured by an orifice plate meter that follows the ISO 5167*98 norm (Delmée, 2003). The atomization air flow was measure by two rotameters, the first one had a scale of 0 to 0.08 g/s ± 1% and the second one had a scale 0 to 0.20 g/s ± 1%. The fuel flow rate was also measured by two rotameters, ethanol rotameter which had a scale of 0 to 1.2 g/s ± 1% and the diesel rotameter which had a scale of 0 to 0.8 g/s ± 1%. Water flow was measure by a rotameter with a scale of 0 to 4 gpm ± 2%. Combustion gas composition was measured by a system formed by the following analyzers: UHC (0 to 100 ppm ± 1%), NOx (0 to 10.000 ppm ± 0.5%), CO (0 to 5% ± 1%), the temperatures of the combustion chamber, the fuel, cool water, and atomization air was measured by chromel alumel termocouples (type K) with scale of 0 to 1200 °C ± 2,2 °C. The Temperatures and the combustion gas composition were registered in a data acquisition system.

In tests, the heat power released by each fuel was 21 kW. This value corresponds to a diesel flow rate of 0.5 g/s. Due to the lesser calorific value of ethanol its flow rate was of 0,852 g/s.

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RESULTS AND DISCUSSION

The consistency of the obtained data was corroborated by applying a mass balance to the different experiments regarding diesel and ethanol combustion. The coefficient of air in excess was obtained in two ways, a direct calculation which uses the measured values of fuel and air mass flow rates, and, an indirect calculation which uses the measured composition of the combustion gas into the global one-step combustion reaction. The results revealed a measurement error of 1.59% in diesel case and the 1.8% in ethanol case.

The value of pollutant emissions showed in figures was corrected to 3% of O2 volumetric concentration, using the procedure presented by Carvalho and McQuay (2007).

Effect of the Atomization Ratio on the Burning Processes

The atomization ratio is defined as the ratio of atomization air mass flow rate to fuel mass flow rate. The effect of the atomization ratio on the burning processes of diesel and ethanol is studied in this section.

Lacava (2000) and Mullinger (1974) shown that the atomization ratio Rat is the most important parameter to evaluate the atomization in the Y-Jet atomizers. The air stagnation pressure is another parameter used to evaluate the atomization in these atomizers (Couto et al., 1999). In this study both parameters are considered. The CO, UHC and NOx emissions, from diesel and ethanol combustion, are depicted in Figures 5 to 7.

In the diesel case and the two ethanol cases, it is observed that, CO and UHC emissions decrease while NOx emissions increase with improved atomization. This indicate that the improvement in the atomization quality origin the improvement in the combustion. This agrees with results reported by others authors, as Couto et al. (1999) and Carvalho and Lacava (2003).

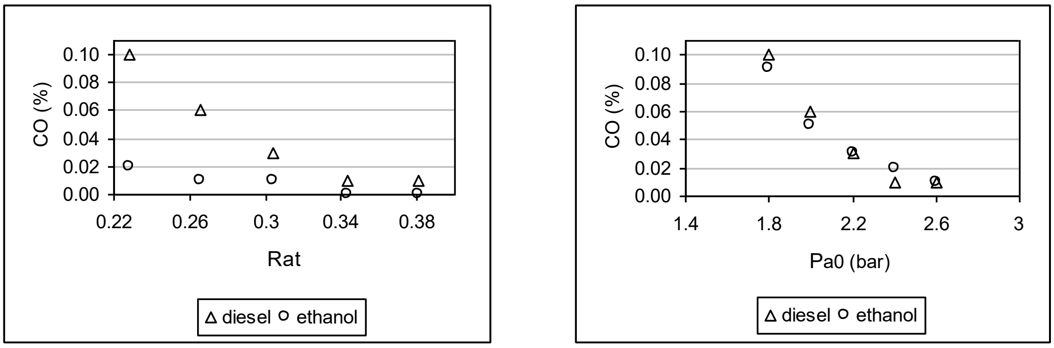
In part (a) of Figures 5 to 7 show the pollutants emissions from the combustion processes at the same atomization ratio Rat. It is observed that the CO and UHC emissions for ethanol combustion are lower than those for diesel combustion, mainly for atomization ratios lower than 0.3. In the case of NOx emissions, ethanol combustion produced lower concentration for all the atomization ratios. The concentration of NOx varied from 65 to 90 ppm, and from 3 to 20 ppm for diesel and ethanol, respectively. The lower emissions of CO and UHC, in the case of ethanol combustion, show that ethanol presents a more efficient combustion process than diesel. This is due to the high volatility of ethanol that increases its mixture rate and consequently improves its atomization.

When ethanol and diesel are atomized with the same atomization ratio Rat, more compressed air is required for ethanol than for diesel combustion (69% more) which leads to an increase of the atomization air-fuel pressure in ethanol case (see Table 2). This fact together with the lesser ethanol viscosity produces a better atomization and combustion in ethanol case than in diesel case. In Figure 5 (a) is also observed that the CO emissions are very low for the ethanol combustion. This can be explained by the better atomization of ethanol and by presence of water in its composition (7% in mass basis). The water presence modifies the CO reaction mechanism, increasing its reaction rate, CO reacts slowly unless hydrogen is present. Small concentrations of H_2 or H_2O can significantly accelerate the CO reaction rate. (Turns, 2000).

The lower emissions of NOx, for ethanol combustion, can be explained by presence of water in ethanol composition, which reduces the flame temperature. According to Lenço (2004), the NOx emissions can be controlled by injecting from 5 to 10% of water (liquid or steam) in the combustion zone of the chamber. In the study carried out by Lin and Pan (2001), the emissions of CO and NOx, from diesel combustion in a marine engine, were reduced by using emulsions of water and diesel (W/D).

Figure 5

CO emisions (a) as function of atomization ratio (b) as function of air stagnation pressure

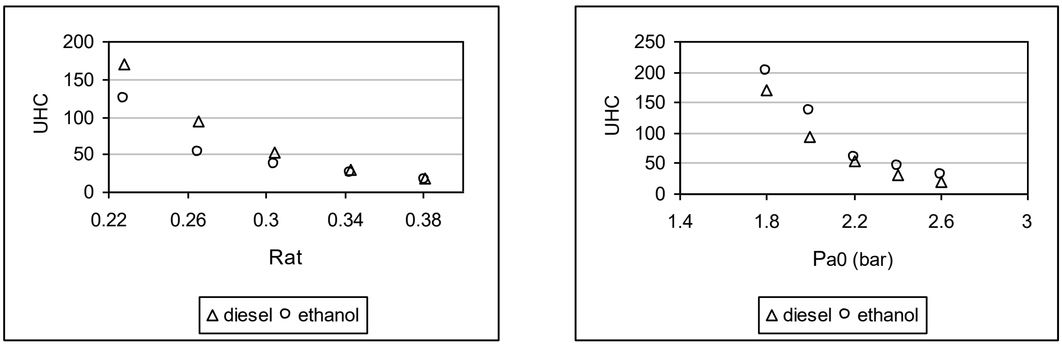


(a) (b)

Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

Figure 6

UHC emissions (a) as function of atomization ratio (b) as function of air stagnation pressure



(a) (b)

Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

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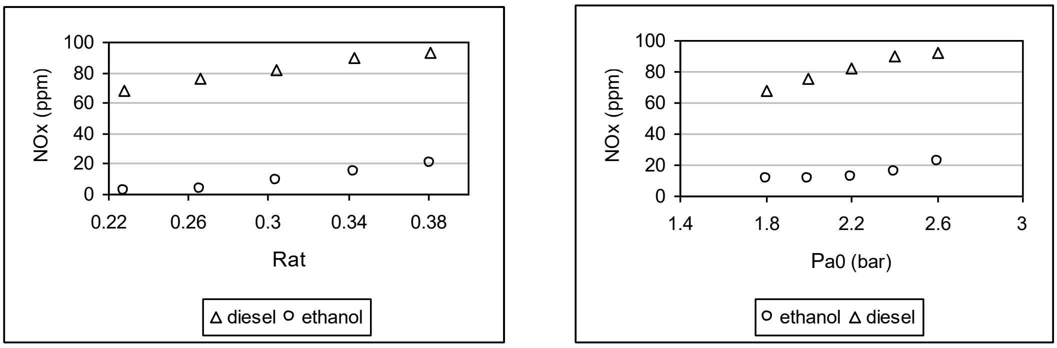
Figure 7

NOx emisions (a) as function of atomization ratio (b) as function of air stagnation pressure



(a) (b)

Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

The pollutants emissions, originated by the combustion of diesel and ethanol, when burned with the same atomization air pressure Pa0, are shown in part (b) of Figures 5 to 7. When comparing the combustion of ethanol and diesel for a Pa0 of 2.2 bar, it is observed that ethanol combustion emitted less NOx, slightly more UHC and slightly less CO. Above an atomization pressure of 2.2 bar the aforementioned behavior is inverted.

The fact that the emissions of CO and UHC are roughly equal for both ethanol and diesel combustion, can be explained with aid of Table 2. When ethanol and diesel combustion take place at the same atomization air pressure, the value of the Rat and the atomization air flow rate are smaller for ethanol combustion. It can be observed that the value of the air mass flow rate for ethanol combustion is between 8 to 28% lower than the value for diesel combustion. Also, the value of the atomization ratio for ethanol combustion is between 46 to 57% lower than the value for diesel combustion. These facts affect negatively the atomization of ethanol and, as consequence, its combustion. Thus, the CO and UHC emissions for ethanol combustion tend to be bigger than those for diesel, but this effect is in part attenuated by the high volatility and lower viscosity of the ethanol.

Tabla 2

Dates of the experiments 1 and 2

	Test: same R_{at}						**Test: same P_{a0}**					
	Fuel			Atomization rate			Fuel			Atomization rate		
N°	Fuel	m_c (g/s)	P_{comb} (bar)	m_{at} (g/s)	R_{at}	P_{a0}	Fuel	m_c (g/s)	P_{comb} (bar)	m_{at} (g/s)	R_{at}	P_{a0}
1	diesel	0.5	0.35	0.12	0.23	0.80	diesel	0.5	0.35	0.12	0.23	0.80
2	diesel	0.5	0.40	0.13	0.27	1.00	diesel	0.5	0.40	0.13	0.27	1.00
3	diesel	0.5	0.45	0.15	0.3	1.20	diesel	0.5	0.45	0.15	0.3	1.20
4	diesel	0.5	0.45	0.17	0.34	1.40	diesel	0.5	0.45	0.17	0.34	1.40
5	diesel	0.5	0.50	0.19	0.38	1.60	diesel	0.5	0.50	0.19	0.38	1.60

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6	ethanol	0.85	1.00	0.19	0.23	1.50	ethanol	0.85	0.70	0.08	0.10	0.80
7	ethanol	0.85	1.15	0.23	0.27	1.80	ethanol	0.85	0.85	0.12	0.14	1.00
8	ethanol	0.85	1.20	0.26	0.3	2.05	ethanol	0.85	0.95	0.13	0.16	1.20
9	ethanol	0.85	1.35	0.29	0.34	2.30	ethanol	0.85	1.10	0.16	0.18	1.40
10	ethanol	0.85	1.45	0.33	0.38	2.50	ethanol	0.85	1.20	0.18	0.21	1.60

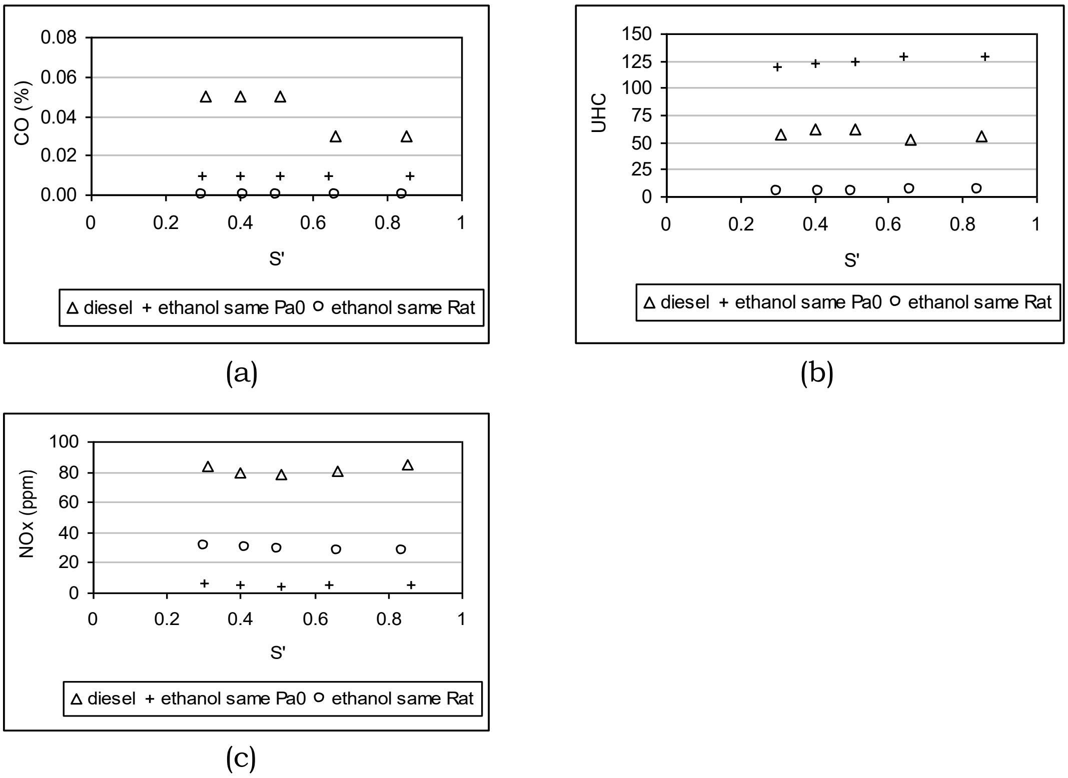
Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

Influence of flame holder

In these tests, it is studied the influence of a flame holder on the pollutants produced by the combustion of diesel and hydrated ethanol. The flame holder used in the experiments was of variable blades swirler type; therefore, the swirl number S' was used as the comparison parameter for analyses of the flame holder effect. The calculation of S' was carried out following the methodology presented by Lacava (2000), together with the data of swirler presented in section 2. The diesel emissions have been compared with ethanol emissions, in terms of the swirl number S', under in two situations: Combustion with the same atomization ratio (Rat) and with the same atomization pressure (Pa0). The results are presented in Figure 8.

Figure 8

Pollutants emissions as function of S'



Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

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In figure 8 it is observed that the CO and NOx emissions from ethanol combustion are smaller than those from diesel combustion in all considered situations. On the other hand, the UHC emissions from ethanol combustion are higher than those from diesel combustion when the same value of Pa0 is used. It is also observed that for diesel combustion, the increase of S' produces a decrease of the emissions of CO and UHC; this fact indicates that the combustion improves with the increase of the swirl number.

In the case of ethanol combustion, increase of S' does not have a noticeable effect on the emissions of CO, it slightly increases the emissions of UHC and slightly decreases the emissions of NOx. These different behaviors are observed because the recirculation created by the swirler improves the combustion of heavy liquid fuels (as diesel) and pulverized coal; however, it does not produce significant improvements for the combustion of volatile liquid fuels (as ethanol) or gaseous fuels (Salvi, 1975).

The diesel, being a not volatile fuel, presents low evaporation rate. Therefore, the swirl effect increases the mixing rate, improving the combustion. In the case of ethanol, which is a volatile fuel, increase of the swirl number does not significantly improve the mixing rate; on the other hand, the considerably increase of swirl number increased recirculation flow enhances flame cooling. In these tests a clear reduction of the temperature was observed at the center of ethanol flame when the swirl number is increased. This lower flame temperature, without any substantial improvement in the mixing rate, produces higher UHC emissions and lower NOx emissions. The CO emission were not increased by the lower flame temperature due to the presence of water.

Influence of the air excess coefficient

In these tests the influence of air excess coefficient b on the pollutants emissions is considered under two situations: Combustion with the same atomization ratio (Rat) and with the same atomization pressure (P_{a0}).

In previous tests the emissions were corrected for 3% of O2. In present tests, there are important variations in the amount of O2; therefore, the curves of corrected emissions would allow to compare the combustion of both fuels, but they would hide the effect of the coefficient of air excess on the pollutants. In order to prevent this, the emissions curves are presented without correction.

In Figure 9 it is observed that ethanol combustion emissions are lower than the diesel combustion emissions, with the exception of the UHC emissions at the same P_{a0}.

Figure 9, shows that, for diesel combustion, the emissions of CO and UHC decrease when b is increased. Therefore, the efficiency of diesel combustion improves with the increase of air excess. On the other hand, for ethanol combustion, the emissions of CO and UHC are almost constant under the two considered situations. The NOx emissions, decrease with the increase of the coefficient of air excess, for the combustion of both fuels.

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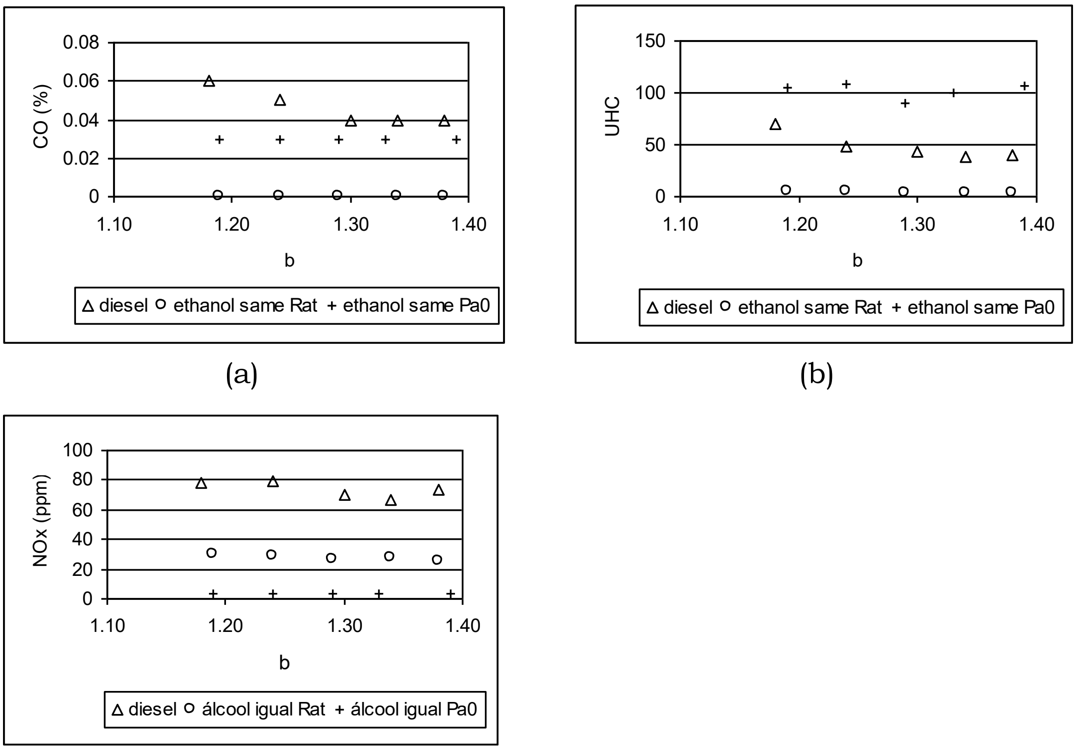
Figure 9

Pollutants emissions as function of S'



(a) (b)

(c)

Note. Adapted from *Replacing diesel used in industrial burners with fuel alcohol* (in Portuguese) [Doctoral thesis, Universidade Estadual Paulista], by E. Paz Pérez, 2007.

Soot emissions and flame characterization

In diesel combustion, considerable soot emissions were observed in the combustion products. The flame presented a completely yellow color. This characteristic is typical of droplet combustion. According to Suzuki and Chiu (1971), diluted sprays of not volatile fuels and big droplets form flames around an only droplet. This type of combustion process is characterized by high soot emissions that give to the flame a yellow color and high radiation. The droplet burning characteristic of the diesel fuel is due to its low volatility, lower fuel flow rate and higher viscosity. These two last characteristics lead to the formation of bigger droplets.

In contrast, ethanol flame presents a blue color in the axial region next to the injector, and white and palish orange tonalities in the other regions. In ethanol combustion, it is not observed significant soot emissions, except small ones when the conditions were most unfavorable for the combustion. This type of combustion process is characteristic of group combustion. In this one, a flame burns around a droplets cloud. The group combustion is form in dense sprays with small droplet diameters and volatile fuels. A cluster of flames are homogeneous, similar to the gaseous diffusion flames. Therefore, not forming soot, the particulate material presents blue color. Due to the absence of solid particles, this kind of flame is little radiating.

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This combustion behavior is typical of group combustion, where the flame forms around a cloud of fine droplets. It occurs in dense sprays composed of small droplet diameters and volatile fuels. The resulting flame is homogeneous and resembles a gaseous diffusion flame. As it produces little to no soot, the flame exhibits a blue color due to the absence of solid particles, and its radiative intensity is low.

Due to the high volatility of the ethanol, its good atomization, and, greater density of its spray (it needs greater amount of fuel due to its low heating value); it is expected group combustion type for ethanol. Experimental studies confirm this hypothesis. In the work of Lenço (2004) it is observed that ethanol flame is blue, without the presence of soot and with low radiation intensity. According Machiroutu (2001) ethanol flame was characterized as an internal group combustion.

The ethanol combustion presents two more advantages with respect to diesel combustion, apart from the lower pollutants and soot emissions already discussed:

- Lower CO2 emission. Since ethanol is obtained from sugar cane (in Brazil) the carbon emissions of CO2 are compensated during the growth stage of the sugar cane. Therefore, on the general balance of ethanol life cycle, it effectively does not add CO2 during its burning, but during the stages of production and transport.
- Ethanol combustion does not emit SO2. On the other hand, the diesel combustion emits 166 g of SO2/GJ-diesel.

It is important to observe that to get a satisfactory substitution of diesel for ethanol the following aspects must be considered:

- To use the ethanol in the same combustion system than diesel, the fuel pump must be changed. In the burners that use oil diesel, the fuel injector pumps are of positive displacement type, which are lubricated by the fuel itself. The kinematic viscosity of ethanol (to 300 K), is approximately half than the diesel viscosity (1.78 and 3.707 cSt respectively). Due to its low viscosity, ethanol cannot be used as lubricant for the injecting pumps. Therefore, it cannot be used directly without changing the fuel pump.
- In systems that use ethanol as fuel precautions must be taken to prevent losses by evaporation and fire risks. Due the ethanol high volatility, the possibilities of fuel evaporation lost are higher. Ethanol can form flammable mixtures at lower temperatures than diesel, the flash point of the hydrated ethyl alcohol is 15°C while that for the diesel he is 38, °C.

These results can be summarized in that the high volatility of hydrated ethyl alcohol, the presence of water and the OH radical in its composition contribute to considerably lower pollutant emissions than those corresponding to diesel. This shows that ethanol is an interesting substitute for diesel in direct burning as industrial burners and gas turbines.

This research is limited to the characteristics of Brazilian vehicle fuels, mainly hydrated ethanol, which has a water content of approximately 7%, a compound that has a great effect on the reduction of pollutant emissions from burning. It is suggested that other countries repeat the experiments with their own fuels. Also, the present work is limited to Y-Jet type atomizers and swirler type stabilizers.

CONCLUSIONS

This research confirms that hydrated ethyl alcohol can be used as a viable alternative to diesel in the same combustion system, achieving a substantial reduction in emissions of CO, NOx, and particulate matter. The only technical adjustment required is the replacement of the fuel pump, due to the lower viscosity and lubricity of ethanol compared to diesel.

The lower NOx emissions observed during ethanol combustion are mainly due to the water content in the fuel, which decreases flame temperature. Likewise, the significant reduction in CO and particulate matter emissions is attributed to ethanol's high volatility and the presence of water and OH radicals, which promote more complete combustion.

In addition to these advantages, ethanol combustion does not produce sulfur dioxide (SO_2), and the CO_2 emitted is largely compensated by the carbon absorbed during the sugarcane growth cycle. Therefore, ethanol contributes to a lower net carbon footprint, with emissions mainly associated with its production and transportation.

Finally, the combustion behavior differs notably between the two fuels. Diesel exhibits droplet combustion, with a yellow flame and high soot generation, while ethanol displays cluster combustion, producing a blue flame with minimal soot. Based on these findings, future studies are recommended to evaluate ethanol performance using other injector types, such as pressure swirl atomizers, and to test its application in gas turbine combustion chambers.

Rol de contribución

Edgar Paz: Conceptualización, análisis formal, investigación, escritura –revisión y edición, visualización, supervisión.

João Carvalho: Conceptualización, curación de datos, recursos, escritura –borrador original.

German Chumpitaz: Conceptualización, curación de datos, recursos, escritura –borrador original.

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