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ANÁLISE ENERGÉTICA E ECONÔMICA DA UTILIZAÇÃO DO ETANOL HIDRATADO

ENERGETIC AND ECONOMIC ANALYSIS OF USE OF HYDRATED ETHANOL

RUOSO, Ana Cristina[1]; LHAMBY, Andressa[1]; MISSAGGIA, André Brum[1]; KLUNK, Marcos Antônio[2]*; CAETANO, Nattan Roberto[1]

[1] Federal University of Santa Maria, Roraima Av. 1000, 97105-900 Santa Maria, RS, Brazil

[2] University of Vale do Rio dos Sinos, Unisinos Av. 950, 93020-190 São Leopoldo, RS, Brazil

** Correspondence*
e-mail: marcosak@edu.unisinos.br

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RESUMO

O interesse em biocombustíveis está crescendo e o etanol tem sido o biocombustível mais utilizado como aditivo e substituto da gasolina, sendo considerado uma alternativa potencial aos combustíveis tradicionais. O etanol representa 17% do consumo de energia em transporte no Brasil, a participação do setor de transporte na matriz energética é de 32,4%, que é o segundo setor que consome mais energia. A produção de etanol de primeira e segunda geração na mesma planta industrial apresenta melhores resultados econômicos em comparação aos processos isolados. Além disso, o etanol obtido da cana-de-açúcar apresenta biodegradabilidade e propicia a mitigação das emissões de CO_2. O objetivo do trabalho é realizar uma análise do etanol com vários níveis de hidratação, em termos energéticos, econômicos, ambientais e de segurança. Os resultados mostraram que a cada 10% de água em diluição em etanol, a temperatura na chama ao redor diminui 4%. Além disso, o etanol com 20% de diluição em água emite 20% menos radiação em comparação com 10% da diluição em água. De fato, a energia consumida na destilação para produzir etanol com 10% de água é o dobro. Por outro lado, essa diferença de energia na produção de etanol diluído com 30% de água não é suficiente para compensar as perdas no processo de uso de energia. Além disso, grandes quantidades de água na diluição do etanol podem inviabilizar o uso devido ao custo total do transporte. Portanto, o etanol com 20% de água representa o combustível mais eficiente, limpo e seguro em aplicações de chama livre.

Palavras-chave: *Bio-combustível, Biomassa, Uso da Energia, Combustão Segura, Cana-de-açucar.*

ABSTRACT

Interest in biofuels is growing, and ethanol has been the most used biofuel as an additive and as a gasoline substitute and, it is considered a potential alternative to traditional fuels. Ethanol represents 17% of energy consumption in transportation in Brazil, the transport sector's share in the energy matrix is 32.4%, which is the second most energy-consuming sector. The production of first and second-generation ethanol in the same industrial plant presents better financial results compared to the isolated processes. Also, ethanol obtained from the sugarcane has renewability, biodegradability and provides CO_2 emissions mitigation. The objective of the work is to perform an analysis of the ethanol with several levels of hydration in terms of energetic, economic, environmental and safety. The results showed that each 10% of water in ethanol dilution the temperature in the flame surround decreases by 4%. Besides, the ethanol with 20% of water dilution emits 20% less radiation compared to 10% of water dilution. Indeed, the energy consumed in the distillation to produce ethanol with 10% of water is double. On the other hand, this energy difference in the production of ethanol diluted with 30% of water is not enough to compensate for the losses in the energy use process. Also, large amounts of water in ethanol dilution might be unfeasible the use due to the total cost of transportation. Therefore, ethanol with 20% of water represents the more efficient, cleaner and safe fuel in free flame applications.

Keywords: *Biofuel, Biomass, Energy Use, Combustion Safety, sugarcane.*

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1. INTRODUCTION

Concerns about climate, environmental, technological, economic, political, demographic and social changes directly affect the world energy matrix (Shah *et al.,* 2019; Cataluña *et al.,* 2018; Moraes *et al.,* 2014). Interest in biofuels is growing, and ethanol has been the most used biofuel as an additive and as a gasoline substitute and, it is considered a potential alternative to traditional fuels (Chuepeng *et al.,* 2016; Goldemberg *et al.,* 2014; Breaux and Acharya, 2013; Nigam and Singh, 2011; Haq *et al.,* 2016). Ethanol represents 17% of energy consumption in transportation in Brazil, the transport sector's share in the energy matrix is 32.4%, which is the second most energy-consuming sector (EPE, 2017; Belincanta *et al.,* 2016). Hydrated ethanol had a share of 19.3 billion liters, at an alcoholic content range between 92.5 and 93.8° INPM (CONAB, 2016; Caetano *et al.,* 2015a).

The practical use of hydrated ethanol represents an essential factor for the reducing costs related to the energy consumed in the process (Venturini *et al.,* 2018; Tura *et al.,* 2018; Matugi *et al.,* 2018; Robertson and Pavlath, 1985; Fagundez *et al.,* 2017; Cataluña *et al.,* 2017). The production of first and second-generation ethanol in the same industrial plant presents better financial results compared to the isolated processes (Silva *et al.,* 2017; Caetano *et al.,* 2015b; Dias *et al.,* 2012; Ojeda *et al.,* 2011; Seabra *et al.,* 2010). Also, ethanol obtained from the sugarcane has renewability, biodegradability and provides CO_2 emissions mitigation (Klunk *et al.,* 2018a; Ponomarev *et al*., 2017; Caetano and Silva, 2017; Tura *et al.,* 2018; Idrees *et al.,* 2014; Banerji *et al.,* 2014; Quintero *et al.,* 2008).

In social aspects, the advantage is due the processes involved in ethanol production create up to four times more jobs if compared with fossil fuels (Ruoso *et al.,* 2019; Pollin *et al.,* 2008). The ethanol from sugarcane generated six times more jobs than oil fuel (Farina *et al.,* 2013). Regarding the safety of use and storage, fires with ethanol represent dangerous situations for surrounding structures and people (Fossa and Devia, 2008). The flashpoint limit is an essential factor for the fire's prevention and unexpected explosions because this point is inversely proportional to the water concentration at the ethanol produced (Velásquez *et al.,* 2017).

The ethanol production stages are investigated continuously in order to obtain optimizations related to energy consumed in the biofuel life cycle (Khatiwada *et al.,* 2016; Bansal *et al.,* 2016). The distillation stage has great industrial importance since its energy consumption is high (La-Salvia *et al.,* 2015; Jana, 2014). In this way, the optimization of the operating conditions in the distillation stage contributes to economic success (Klunk *et al.,* 2019a; Saffy *et al.,* 2015; Werle *et al.,* 2009).

The energy required to distill a mixture of up to 80% ethanol in water shown linear behavior. However, an abrupt increase in energy consumption is observed at concentrations up to 80% of ethanol (Fagundez *et al.,* 2017; Rahman *et al.,* 2016). As it is up to 95.6% by volume of ethanol, the energy for dehydration increases exponentially, raising the final value of the product (Aceves and Flowers, 2007; Mayer *et al.,* 2015; Pal *et al.,* 2018). The energy consumed in ethanol distillation with a concentration of 95% corresponds to 50% of the energy contained within the ethanol (Pimentel and Patzek, 2008).

Figure 1 shows the energy consumed in the distillation industrial phase in the function of the ethanol concentration in water. The costs of distillation for the ethanol production, with up to 80% ethanol in water, accounts for 20% of the total costs related to the energy used in the processes (Robertson and Pavlath, 1985). From this point, the distillation and dehydration processes account for approximately 37% of the energy production costs (Breaux and Acharya, 2011). In environmental terms, the use of biomass contributes to the low emissions of carbon dioxide (CO_2) (Klunk *et al.,* 2019b; Klunk *et al.,* 2018b; Klunk *et al.,* 2017a; Demirbaş, 2004). These low carbon dioxide emissions can be predicted by geochemical modeling (Klunk *et al.,* 2019c; 2019d; 2019e; Klunk *et al.,* 2018c; Klunk *et al.,* 2017b; Klunk *et al.,* 2015).

The use of ethanol as fuel or additive also reduces the CO_2 emissions when compared to fossil fuels (Melo *et al.,* 2012; Wang *et al.,* 2015). The CO_2 emitted burning biomass products are recycled through photosynthesis, which acts on biomass growth (Mandegari *et al.,* 2018; Zhang *et al.,* 2010). Thus, biofuel use has reduced carbon emissions by 10% throughout the energy sector (Flórez-Orrego *et al.,* 2015; Szklo *et al.,* 2005).

Ethanol, with 20% of water, shown a significantly increase in thermal efficiency (Chuepeng *et al.,* 2016). Meanwhile, 30% of water in ethanol represents an optimum dilution, being the most energy-efficient fuel to be produced, with the best actual use of the available chemical energy. Also, it presents

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advantages in terms of energy balance and cost reduction (Fagundez *et al.,* 2017). Perhaps, this concentration should provide a large amount of water to transport in dynamic applications. Also, the heat release for ethanol from 96% to 100% is approximately the double of the values measured for 50% ethanol, so the radiation is directly proportional to the ethanol concentration (Hakkarainen *et al.,* 2017).

Therefore, this work aims to perform energy, economic, environmental, and safety analysis on the use of hydrated ethanol, considering the whole ethanol cycle, from planting to energy production. Thus, there is an interest in determining the relationship between the energy consumed in the production process and the calorific fuel value, the most representative production total costs, environmental factors, safety assurance, and, finally, concentration hydrous ethanol for industrial applications.

2. MATERIALS AND METHODS

2.1. Background

Information on sugarcane planting, transport and ethanol production in the plant, as well as energy balance, CO_2 equivalent (eq) emissions, and total costs were obtained from a bibliographic review. The Bibliographic Portfolio selection for this bibliographic study survey consists of three stages: (i) articles bank gross selection; (ii) articles database filtering (Cardoso *et al.,* 2015).

The selection was composed of three main stages: i) keywords definition; ii) database selection; iii) according to the defined keywords search for articles (Ensslin *et al.,* 2012). The results obtained in the literature review were converted according to CONAB, where 76 ton/ha corresponds to 5.928 L/ha, and 68 L/ton corresponds to 0,078m³/ton. Thus presenting uniformity in the measures, and thus it was possible to discuss the results (CONAB, 2016).

In this way, it was possible to identify the stages in which the energy used, the emissions, and the costs were more relevant. Therefore, with the information analyzed, the most efficient ethanol dilution for the pool fire condition was identified.

2.2. Safety analysis

The temperature, combustion rate, and flash point were plotted for the different dilutions of ethanol. The flashpoint was determined to apply ASTM D92-16B (American Society for Testing and Materials, 2016).

In the experimental phase, temperature measurements were performed, and information about the flame was obtained at the different dilutions of ethanol. For this, the hydrated ethanol samples were made with 92% ethanol in water, using a 25 mL burette (resolution 0.1 mL) and KERN weighing-machine (resolution 0.001 g).

The tests used the samples had the following concentrations of ethanol in water: E90W10, E80W20, E70W30, E60W40, E50W50, E40W60, E30W70. A cylindrical aluminum vessel, 14 mm high (h) and 64.98 mm diameter (D), was used to perform the pool fire since the pool fire experiment is defined as a flame that has its spread established on top of a fuel surface (Nakakuki *et al.,* 2002; Sikanen and Hostikka, 2016).

Note that, the flame was under environmental conditions and over an open surface. Three-point thermocouples were used at distances of D/8, D/4, and D/2 from the edge of the fuel container and also at two points in height h and h + D/2, at the same distances in order to measure the ambient temperature in the vicinity of the flame. The thermocouples used were of the K model due to the suitability to the environment (from -270 ºC to +1200 ºC), the high sensitivity (41 mV/ºC) and the associated low measurement uncertainty (0.75%) (Kus *et al.,* 2015; Fialho, 2013).

A camera and a thermal imager were employed to identify flame visual characteristics, such as color, brightness, radiation intensity, and shape. The FLIR model TG165's thermal imager is also 50 x 60 pixels resolution, and it measures temperatures ranging from - 25 to 380 °C, with an accuracy of 1.5%, with a minimum distance of 26 cm.

2.2.1. Radiation

The Radiation is often expressed as a fraction of the total rate of heat release and is vital for the burning rate determination, which is the mode of dominant heat transfer in large scale fires (Fialho, 2013; Hu, 2017; Yang *et al.,* 2017; Chatterjee *et al.,* 2011). Thus, the thermal radiation of the pool fire depends on the combustion products, CO_2, and water, which after the reaction, are at high temperatures, and soot particles (Drysdale *et al.,* 2011).

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Therefore, to determine the dosage of radiation during a time interval of exposure and minimum safe distance for people and equipment, Equations 1 and 2 are used. The radiation dosage was obtained with Equation 1. The radiation dose is represented by J (W/m²), and the energy portion radiates given by Q_R (W).

$$J = \int Q_R^{4/3} d_t \quad \text{(Eq. 1)}$$

From this equation, in addition to the radiation dosage, it is possible to determine the maximum exposure time and distance to safeguard people and materials. The radiation dose of 5 kW/m² can be tolerated during one minute Lowesmith *et al.* (2007). Also is recommended that objects and operators remain at a minimum distance "d" from the source in order to control the exposure, represented by Equation 2, according to the American Petroleum Institute (API, 1969; Caetano *et al.,* 2018; Caetano *et al.,* 2015c).

$$d = \sqrt{\frac{Q_T \tau F_R}{4 \pi q_r}} \quad \text{(Eq. 2)}$$

In Equation 2, τ corresponds to the transmissivity of the medium, dimensionless, q_r is the radiation that the object is exposed (W/m²), and Q_T is the total energy emitted (W) (API, 1969). The energy fraction of the flame that is emitted into the environment is expressed by F_r.

3. RESULTS AND DISCUSSION

3.1. Data collected from the literature

For all the databases selected, a search was carried out with the keywords, with the search fields title (summary) and keywords (keywords). It had a temporary delimitation of 10 years (from the year 2010 to 2017), only publications of scientific articles, thesis, monographs, and dissertations. The files were selected without a database were submitted to a test of adherence and representativeness of the files, and filtering of the database was performed, and thus, the bibliographic file was presented, a later step consisted in the process of debugging the articles selected.

3.1.1. Energy balance

The bibliographic review was compiled in the agricultural phase, industrial phase, and the ethanol distribution phase, corresponding to approximately 54, 28, and 18%, respectively. The energy of the agricultural phase includes the share of energy consumed by planting, cultivating, harvesting, and transporting. Also, it was evaluated the spending on machines, diesel oil, fertilization, seeds, herbicides, insecticides, transport of inputs and cane. The cultivation of sugar cane requires an area preparation for six consecutive harvests. This yields low energy utilization at this stage when compared to the energy available from ethanol (Salla *et al.,* 2010). Figure 2 shows the energy balance of ethanol, according to some authors.

The values presented a discrepancy, i.e., until nine units of renewable energy per unit fossil energy, are due to the particularities considered by each researcher. These are related to the year, the use of bagasse, energy cogeneration, planting regions, the size of the plants, distribution of biofuel, facilities, maintenance, labor, among other components.

However, considering 30% of the sugarcane bagasse was used for the replacement of wood in the boiler plants so that the rest of the bagasse was used in silage production Turdera *et al.* (2013). Also, it was evaluated the energy used for the production of ethanol in five different plants, obtaining an average energy balance of 6.8. The author considered the energy consumed in the distribution phase of ethanol as 2.82 GJ/ha. This distribution is made from the plant to the ethanol distribution stations. In addition, the author considered only the production of energy resulting from the use of ethanol, not considering the production of surplus electricity and the use of excess bagasse.

Donke *et al.* (2017) obtained values around 40% higher than García *et al.* (2011) and Donke *et al.* (2017). However, it was considered for the calculation the cogeneration, and the production process multipurpose plant of this study may have had better performance because it ignores the infrastructural aspects and occurs considering a technology. Besides, this case study was conducted in a region where sugarcane production is only expanding, which can result in above-average performance. Also, García *et al.* (2011) is a study carried out in Mexico using direct juice ethanol using bagasse and generating surplus electricity from cycle five years with 70 t/ha.

Fuel consumption by agricultural machinery is 22.3 L/ha/year of diesel

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corresponding to 1,062.7 MJ/ha (Soares *et al.,* 2009). The majority of this fuel is used in the implantation of the crop. In addition, transportation of sugar cane from the field to the plant has a high fossil fuel expense, corresponding to 2,058 MJ/ha/year (Boddey *et al.,* 2008).

The industrial phase considers the processes of extraction and treatment of the liquid from the sugarcane pressing, fermentation, distillation, dehydration, and maintenance. A large amount of energy is used in the phases of cleaning, crushing of the raw material, mats, and heating of the raw material in the plant. The global efficiency of the sugar cane ethanol production process is about 70%. The main losses are in the vapor generation and distillation, with 30% each (Saffy *et al*., 2015). Besides, sugarcane straw and bagasse from the plantation can be used directly to produce energy. This biomass waste is burned in boilers to generate energy, in biodigesters, or for the production of second-generation ethanol (Leal *et al.,* 2013; Sordi *et al.,* 2013). Another essential factor of the use of biomass is to include the residues in the process of synthesis of zeolites to be used in industrial processes (Klunk *et al.,* 2020; Klunk *et al.,* 2019f).

The energy used in ethanol distribution increases representatively with the distance traveled by the finished product from the plant to the destination. Thus, in order to simplify the studies, most authors do not consider the distribution phase of ethanol for the evaluation of the energy used in the ethanol cycle, as this can vary widely due to the conditions in different regions.

Besides, these values also vary according to ethanol dilution. According to work (Kun-balog *et al.,* 2017), the production of the E92W8 instead of the E96W4 results in an energy saving of 154%. Also, the production of less concentrated ethanol such as the E52W48, increases this energy savings by 169%. An economy of 31% on the energy consumption was verified in comparison regarding ethanol E0W20 and anhydrous applied in an engine (Lanzanova *et al.,* 2016). López-Plaza *et al.* (2014) shown that 30% of energy economy can be reached using E80W20, while Saffy *et al.* (2015) indicates that the best rate is E86W14 due the thermal energy consumption, which is reduced in 10% (from 7.7 to 6.9 MJ/L), then, the financial energy spends decrease 8% in comparison to the anhydrous. The difference between the authors' results is a consequence of the production process which Saffy *et al*. (2015) use corn in a sub-tropical country. Therefore, the production of hydrated ethanol can significantly increase the energy balance.

3.1.2. Dioxide equivalent emissions

Greenhouse gas (GHG) emissions from the entire ethanol production chain were evaluated in terms of CO_2 eq. The eight articles found containing emission results were compiled in Figure 3. These surveys considered emissions from direct consumption of fuels and electricity, emissions from the production of inputs such as fertilizers, herbicides, lubricants, and seeds. In addition to emissions related to the plant during the industrial process and the mechanization level of the harvest.

The majority of the cultivated areas use the burning of the straw for the harvest, and this conventional technique is still used. Soares *et al.* (2009) emissions by the manual harvesting system for burnt sugarcane and raw cane harvesting were compared. The replacement of the burning by the mechanized harvest represented less pollution. In this paper, the average considered the harvest burning and mechanized was 1.1 $kgCO_2$ eq/L and 0,4 $kgCO_2$ eq/L respectively, which represents 60% of reduction in the pollution.

Total CO_2 emissions considering the burning, have obtained 0.6 $kgCO_2$ eq/L, 1.4 $kgCO_2$ eq/L and 1.0 $kgCO_2$ eq/L and 1.3 $kgCO_2$ eq/L respectively by (Crago *et al.* (2010), Guerra *et al.* (2014), Munoz *et al.* (2014) and Donke *et al.* (2017)). However, Crago *et al.* (2010) included in the industrial phase values approximately 84% lower than those of Donke *et al.* (2017), and finally, the total emissions of $kgCO_2$ eq and found values around 53% lower than the other authors.

The aspects that most influenced its outcome were the emissions from the expansion of the agricultural area, the use of diesel oil in transport, and operations Donke *et al.* (2017). Also, the emissions from the burning of the straw in the pre-harvest stage of sugarcane were considered. These works were performed at distinct regions considering the climate and level of mechanization.

Total CO_2 emissions considering mechanized harvesting, obtained 0.2 $kgCO_2$ eq/L, 0.5 $kgCO_2$ eq/L and 0.5 $kgCO_2$ eq/L and 0.3 $kgCO_2$ eq/L, respectively (Paula *et al.,* 2010; Cavallet *et al.,* 2012; Turdera, 2013; Manochio *et al.,* 2017). Indeed, no GHG emission due to the

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use of fossil fuels in the plants that generate the energy itself from the burning of the sugar cane bagasse Manochio *et al.* (2017). Direct CO_2 eq emissions related to bagasse burning and broth fermentation are not considered in the total emission, so the carbon released in the burning and fermentation will be sequestered by photosynthesis and will compose the vegetation during the next crop Manochio *et al.* (2017).

The average equivalent CO_2 emissions were 0.7 kgCO_2 eq/L during the production of ethanol, which corresponds to 3.6 t/ha. Thus, from the perspective of greenhouse gases during the entire production cycle of ethanol, it has been verified that there is a gain since the CO_2 equivalent, which is sequestered is higher than the amount of CO_2 emitted when the emissions generated, by the production of electric energy are not considered. The production of hydrated ethanol E86W14 decreases 8%, and, also, when there is cogeneration, the reduction of emissions reaches 25% in comparison to E100, when compared to gasoline this value reaches 72% (Saffy *et al.,* 2015; Hinton *et al.,* 2018). On the other hand, Kaliyan *et al.* (2011) conclude that the reduction of emissions in the production of hydrated ethanol E80W20 can reach 40%, considering the distribution from planting, which was also verified in the work of Roy *et al.* (2015) and López-Plaza *et al.* (2014). In addition to CO_2 eq emissions during ethanol production, the use of hydrated ethanol shows changes in the concentrations of other pollutants emitted during the burning of the biofuel. NOx emissions decrease by more than 50% when ethanol dilution increases. Meanwhile, CO and hydrocarbon emissions increase significantly from the E60W40, 58% and 267%, respectively, when compared to E80W20 (Munsin *et al.,* 2013). This is because the use of more diluted ethanol has inefficient combustion. However, the E70W30 up to E96W4 ethanol has extremely low and insignificant CO and hydrocarbon emissions when burned. Therefore, the increase of hydration of ethanol up to 30% of water favors the reduction of pollutant emissions (Kun-balog *et al.,* 2017).

3.1.3. Costs

Since the 2007/2008 harvest, the projection of the agro-industrial production costs of the sugar-energy sector has been performed (Bigaton *et al.,* 2015; Bigaton *et al.,* 2016; Bigaton *et al.,* 2017). The forecast of the total costs for the production of ethanol anhydride and hydrate of the 2015/2016, 2016/2017, and 2017/2018 crops of the Central-South region of Brazil was presented.

In predicting the harvest of 2015/2016, the authors indicated that the production mix of the sugar-energy sector was directed to hydrated ethanol. The forecast for 2016/2017 showed that the increase in costs was related to the decline of agricultural productivity and the low level of renewal and aging in the sugarcane plantations.

For the reduction of costs, the main activities required is the cogeneration of electricity Bigaton *et al.* (2016). Thus, the bagasse is burned, generating electricity. Also, the fall in harvested area and productivity in the forecast for the 2017/2018 harvest, as well as the fall in ethanol production costs.

Figure 4 represents the total costs of producing ethanol for some authors and the average costs. The average found among the authors was 3.2 USD/L.

This work realized research with the costs of ethanol production in the agricultural, industrial, and distribution phases were found three articles of the authors Crago *et al.* (2010), Mayer *et al.* (2016), and Manochio *et al.* (2017). The costs related to the agricultural phase were lower compared to the costs of the industrial phase, which depends on the renewal of the sugar cane plantation. The literature has shown that this renewal occurs every six harvests.

The price is a premium press approximately 0.23 USD/L Crago *et al.* (2010). Moreover, the refinery cost is USD 0.17 per liter, and the transportation of the finished product is US$ 0.80 per liter. The cost of USD 0.4 per liter of ethanol is produced by low expenses for raw material cultivation, energy cogeneration, and second-generation ethanol production Manochio *et al.* (2017).

The production of ethanol and the sale of bagasse accounting for investment costs, maintenance, and operating costs, as well as the minimum, average and maximum cost of the raw material Mayer *et al.* (2016). Raw material costs are 0.27, 0.53 and 0.80 USD/L, with a 12% variation. However, the investment cost for a microdistillery with a capacity of 720.0 L/day was estimated at 0.11 USD/L. Thus, the cost of maintenance and operation was 0.33 USD/L, of which this amount is discounting the sale price of bagasse, in which the minimum is 0.03, average 0.05, and maximum 0.08 USD/L. The authors declare that a variation of 50% in raw material

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cost results in a 26% change in the cost of ethanol. It is estimated that the final cost to the consumer is 1.80 USD/L, including ethanol production costs, taxes and profit margin on the producer, distributor and gas station. This makes the product unfeasible compared to the price of gasoline (Mayer *et al.,* 2016).

This sales value proposed by Mayer *et al.* (2016) is around 55% higher than that found by Crago *et al.* (2010), and 77% higher than that found by Manochio *et al.* (2017), due it was considered a micro-distillery and its final value of 1.80 USD/L corresponds to the final price of ethanol Mayer *et al.* (2016). On the other hand, Manochio *et al.* (2017) considered the costs of biomass, processing and conversion rate, excluding transport costs, which contributed to the cost difference between the other authors.

The cost of distribution affects the final price of biofuel. This relationship is influenced by the fact that ethanol production is located mainly in the Center-South region of Brazil. Thus, ethanol can have up to 40% variation in cost due to transport (ANP, 2016).

A relationship between costs, energy consumed, and energy supplied in the combustion by the biofuel were observed. E90W10 provides a reduction of 31% and 19% when compared to anhydrous ethanol and E95W5, respectively. The E80W20 is the dilution with the lowest production cost. However, mixtures between 85% and 90% of ethanol in water have the best operating cost, because volumetric fuel consumption increases with the water content and less efficiency of the engine (Lanzanova *et al.,* 2016; López-Plaza *et al.,* 2014).Thus, it is possible to perform an estimation of the optimum dilution of ethanol in terms of transport, considering general scenery. The energy released can be calculated by active power during the operation time (Fraga *et al.,* 2014; Klunk *et al.,* 2012).

3.1.4. Safety analysis

Safety analysis related to the ethanol combustion temperature, flame temperature with ethanol dilution, burning time and distance to the source, and fire point, according to section Safety analysis and Radiation.

Figure 5 shows the ethanol combustion temperature, which is related to energy. The temperature is related to the radiation and the transmission of heat by the radiation mechanism to the surroundings.

The ethanol dilution increases the temperature in the surroundings decreases by approximately 4% for each step measured, i.e., 10% (Figure 5). This relationship between dilutions and the reduced temperature is also observed in the work of Li *et al.* (2019). At the distances D/2 and D/4, the temperature behavior is similar, having a difference of approximately 10 °C. At the distance D/8, which is closer to the flame, the temperature increases by approximately 20 ºC of D/4 and 30 ºC of D/2, as well as a more pronounced increase concerning the dilutions.

The use of fuel ethanol with high hydration (above 5% v/v of water) leads to a reduction in the calorific value of the fuel, consequently increasing the energy fraction corresponding to the latent heat of water vaporization and increasing the fuel consumption (Breaux and Acharya, 2011). That way, the temperature of the hydrated ethanol is lower than that of pure ethanol, which is 1920 ºC (Balki and Sayin, 2014). Thus, it is verified the measured temperatures shown in Figure 5, since, in addition to the hydration, the value was obtained around the flame.

The flashpoint limit depends on several factors, such as temperature. In order to evaluate the influence of temperature on the flashpoint limit, only the temperature was modified. The temperature at this point is not responsible for the instantaneous combustion of the whole volume of liquid, because, for the ignition, some external energy supply is necessary.

Mixtures at lower dilutions reach the flashpoint at temperatures lower than ambient, while more diluted mixtures should be heated to reach that point. This information is essential for maintaining the storage safety of ethanol and for defining which dilution of ethanol is most appropriate for storing, in order to prevent fire incidents around the storage areas.

Figure 6 shows the flashpoint in the function of dilutions from the 90% to 30% of ethanol in water, at where noteworthy that the E30W70 sample was heated up to the environment temperature for the definition of the flashpoint.

Figure 7 represents the behavior of the burning time as a function of the ethanol fraction in water. The firing time corresponds to the duration of the combustion until all the ethanol present in the mixture is consumed, or until the mixture becomes so weak that even the high-temperature values of the mixture are not

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sufficient to achieve the flashpoint limit. The samples with higher water presence burned faster and represented dilutions that would give more safety in storage environments. Also observed by Oliveira *et al.* (2019), in which the simulated burning time was almost three times greater than the experimental time for hydrated ethanol. For Rahman *et al.* (2016) the addition of 30% or more of water has a significant influence on the initial combustion reaction and on the burning rate, the presence of small amounts of water (20% or less) resulted in faster combustion. The results presented by the authors are consistent with those presented in Figure 7.

Figure 8 represents the percentage difference of radiant energy by the flames at different dilutions, regarding the sample E90W10 as a reference to the comparison. The tests were performed with a free flame at ambient temperature and pressure. The calculation of the radiant energy depends on the shape, the emissivity, and the temperature. The shape factor is very susceptible to changes in the structure of the flame, as well as emissivity. Therefore, the approximate values of these parameters were estimated and considered constant for all the cases approached in this study, since they exert less influence on the results when compared with the temperature.

The difference in radiation between ethanol E90W10 and E80W20 is approximately 20% and approximately 50% for E70W30. The exposure time and distance react non-linearly for the dilutions presented. In mixtures with higher concentrations of ethanol, the water passed from the liquid to the vapor state and irradiated with the ethanol. In the case of the more dilute ethanol, the water remained liquid and did not radiate, cooling the flame and lowering the radiation.

Besides, the radiation is proportional to the flame volume. The container in which the ethanol was burned was a small container with a small sample. With the percentages between the dilutions of ethanol, it is possible to estimate the adequate exposure time and distance, aiming at safeguarding operators and equipment, according to the ratios and dose limits mentioned in Radiation, Equations 1 and 2. Figure 9 represents the maximum exposure time in minutes.

The maximum exposure time in fire situations to safeguard people and equipment increases with increasing ethanol hydration, as shown in Figure 9. This is because increasing the hydration of ethanol decreases the dosage of radiation and consequently increases the exposure time to this dosage. Just as the more distant a person or equipment is from the flame, the smaller the radiation dosage emitted by the flame, so the longer the exposure time can be compared to distances closer to the flame.

For example, in the case where the radiant energy of the higher flame temperature was around 700 W/m², the operator could remain exposed to the flame for about 7 minutes to E90W10. While for the radiant energy of the E40W60 in the D/2 position was approximately 520 W/m², with a maximum exposure time of approximately 10 minutes.

Considering the laboratory conditions, the distance calculated for the flame of the experiment, according to API (1969), it was millimeters. For the situation that presented higher radiation dosage, E90W10, the safe distance was 12 mm, already for the E40W60 distance value was 8 mm approximately. The distance decreases with ethanol hydration, the difference between the E90W10 for the E80W20 and the E70W30 is 5% and 10%, respectively. Meanwhile, for high hydrates, this difference reaches 30%.

In this work, the values 0.52 to 0.7 kW/m² were obtained for the flame radiation, 7 to 9 min of exposure time, 12 to 8 mm of safe distance. Values of 10 to 12 kW/m² and from 0.3 to 0.5 min and, also, 12.5 to 37.5 kW/m² and 0.13 to 0.40 min of radiation dosage and maximum exposure time were found by Hakkarainen *et al.* (2017) and Fontenelle (2012), respectively. This indicates that the radiation from the flame is inversely proportional to the exposure time and around the same proportion. However, different levels of irradiance and the depth of the pool considered. While, Fontenelle (2012) performed a simulation of a fire in a storage tank, with real dimensions, which considered some standards such as API 650:2007 (2007) and NFPA 30:1996 (1996). Then, due to the dimensions of the pool of the present work, radiation was obtained around 95% lower and with an exposure time around 96% higher than the other works.

4. CONCLUSIONS

The study was conducted to evaluate the optimal dilution of ethanol and water in terms of storage, transport, and energy use. The analysis of CO_2 emissions was based on studies that evaluated the life cycle for ethanol, in terms of the phases, namely: agricultural, industrial, and

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distribution. Also, the behavior of the limits of inflammability, the burning time and the radiation emission of the flames in relation to the dilution were analyzed.

The distillation of ethanol up to 80% consumes approximately 10% of the energy equivalent to the calorific value to be produced. Ethanol E90W10 consumes about 20% of this same energy, which increases energy consumption in the industrial phase, reducing energy balance and thus increasing the production costs. The distillation sector had the highest direct energy consumption concerning the industrial sector. Therefore, the production of hydrated ethanol reduces energy consumption and, consequently, reduces the costs of these sectors. Thus, this production strategy contributes to the increase of energy efficiency in the distillation stage.

The E80W20 ethanol flames emitted 20% less radiation compared to the E90W10, so considering the safety of operators and equipment, there is a gain in exposure time and the limit distance in case of fire incidents. However, this study suggests that ethanol E80W20 represents a significantly more efficient, cleaner, and safer fuel than the E90W10, regarding free flame applications.

It was also verified that there is no simple model that determines the levels of dilution that generate greater efficiency. The analyzes available in the literature do not follow a standard, and even if the life cycle phases for ethanol are similar, there are particularities in each work that drastically alter the results, such as the harvest, the region of planting, the scale of production, agricultural techniques, use of by-products and distribution of the finished product. Thus, for future work, it is suggested that ethanol tests vary the hydration of the samples every 2%. Also, to use pool fires with larger diameters, and to simulate situations with the influence of the wind, increase of the ambient temperature and change of pressure.

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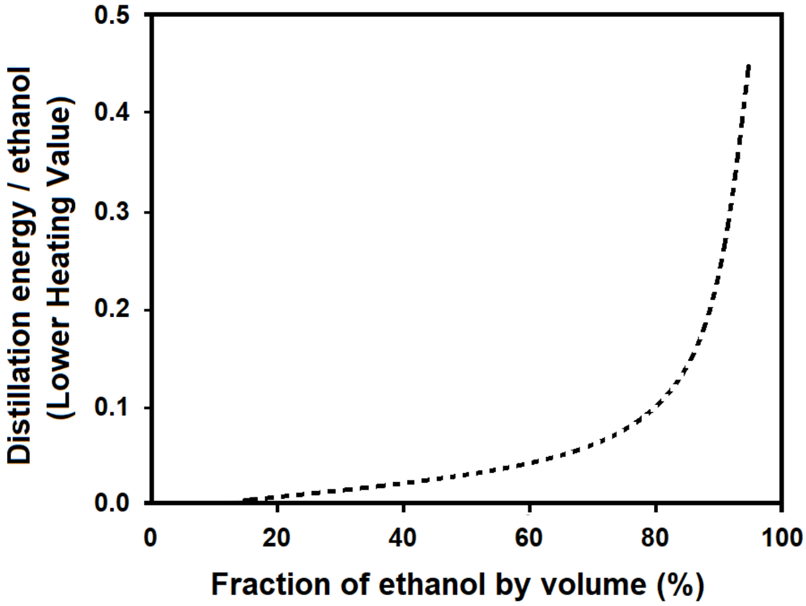

Figure 1. *Energy consumption in the ethanol distillation process (Aceves and Flowers, 2007).*

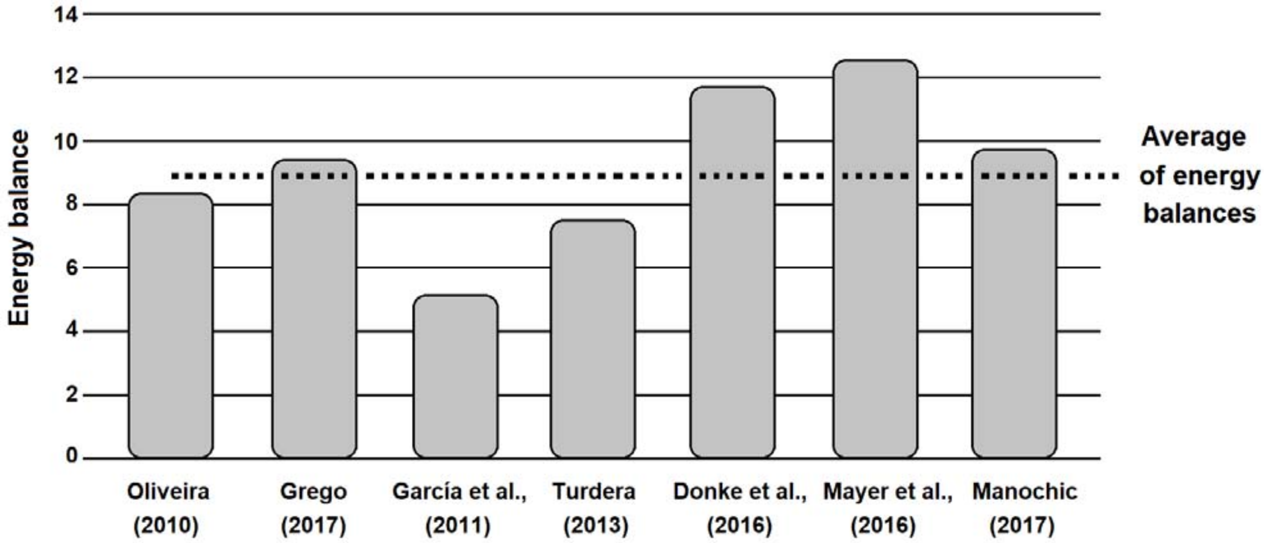

Figure 2. *Energy balance over the last decade, for several authors (Oliveira, 2010; Grego, 2017; García et al., 2011; Turdera et al., 2013; Donke et al., 2017; Mayer et al., 2016; Manochio et al., 2017).*

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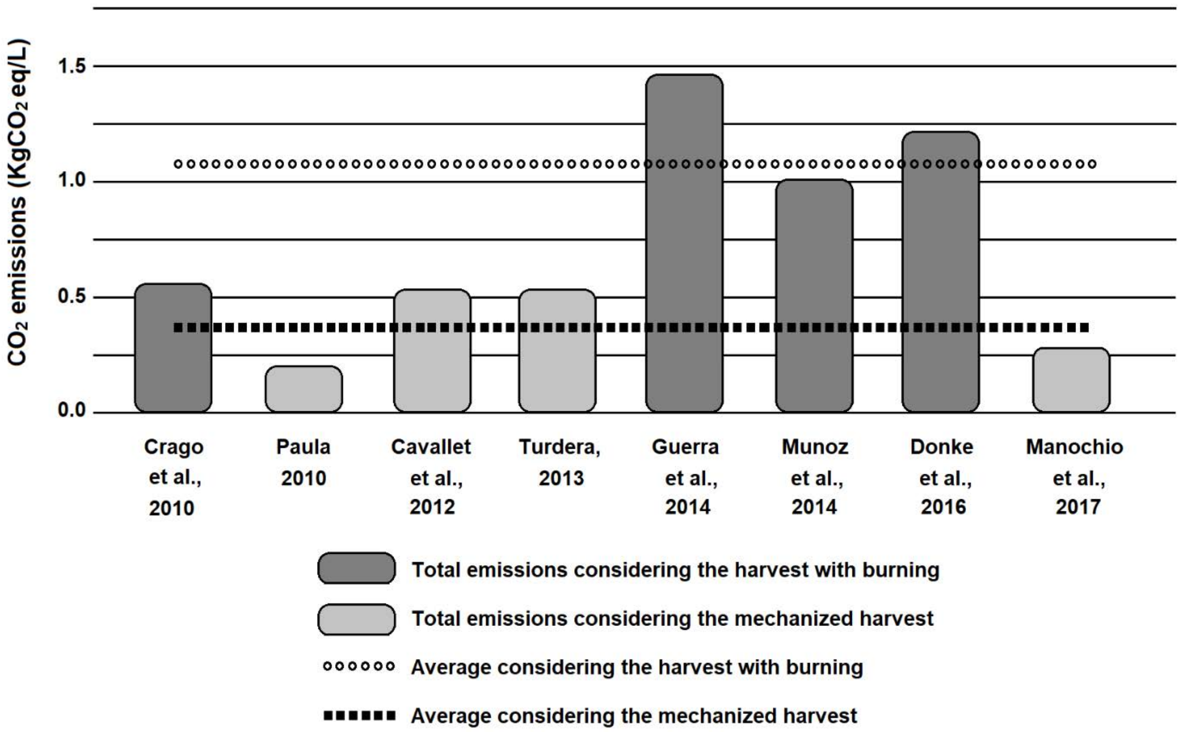

Figure 3. *Total CO_2 emissions (kgCO_2 eq/L) for ethanol production (Crago et al., 2010; Paula et al., 2010; Cavallet et al., 2012; Turdera, 2013; Guerra et al., 2014; Munoz et al., 2014; Donke et al., 2017; Manochio et al., 2017).*

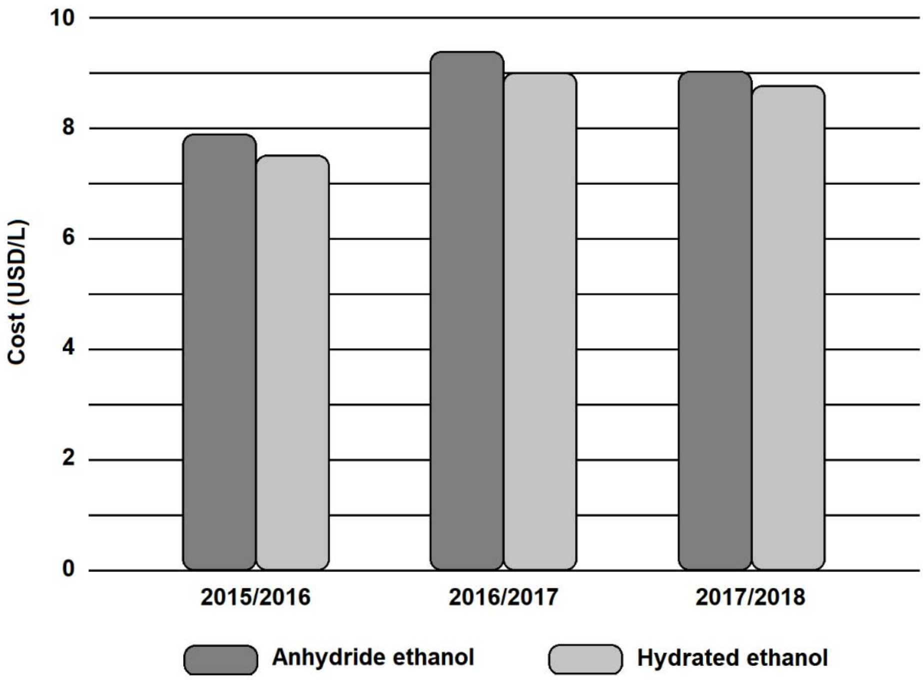

Figure 4. *Total cost forecast for ethanol production (Bigaton et al., 2015; Bigaton et al., 2016; Bigaton et al., 2017).*

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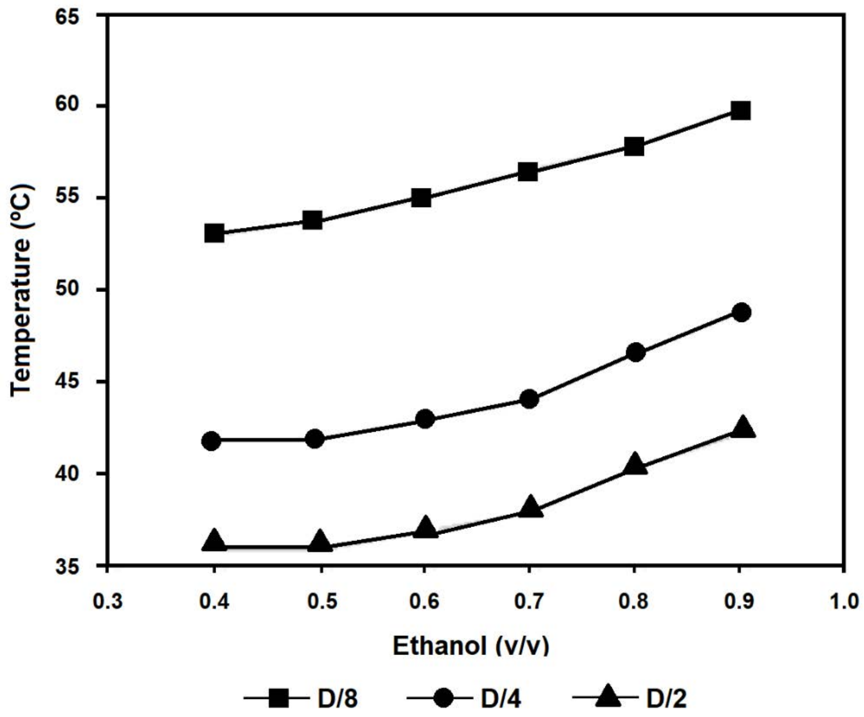

Figure 5. *Surrounds temperature at different distances from the flame.*

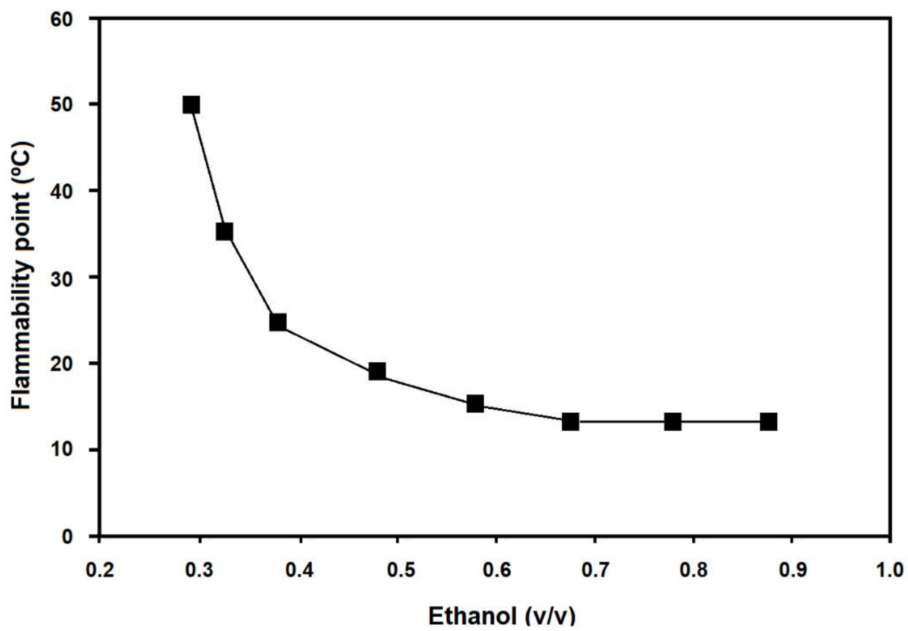

Figure 6. *Flashpoint for dilutions from 90% to 30% of ethanol in water.*

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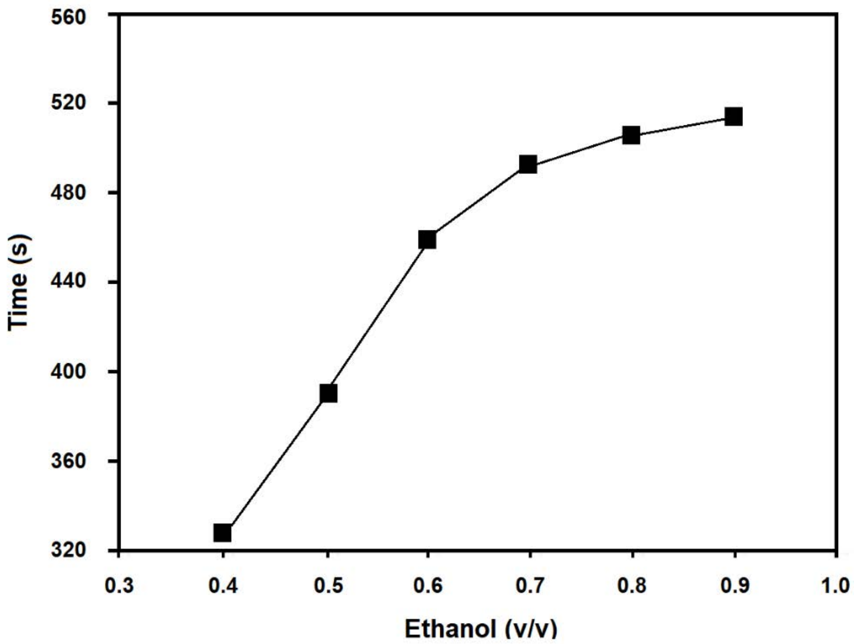

Figure 7. *The behavior of the burning time as a function of the ethanol fraction in water.*

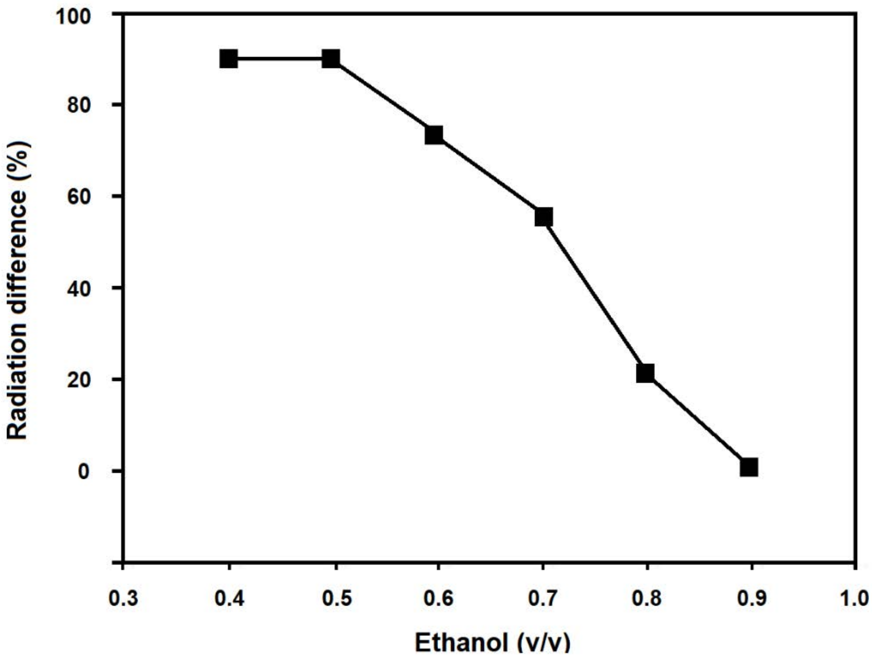

Figure 8. *The difference of radiant energy (RE) between the flames in relation to E90W10 with the other dilutions of ethanol.*

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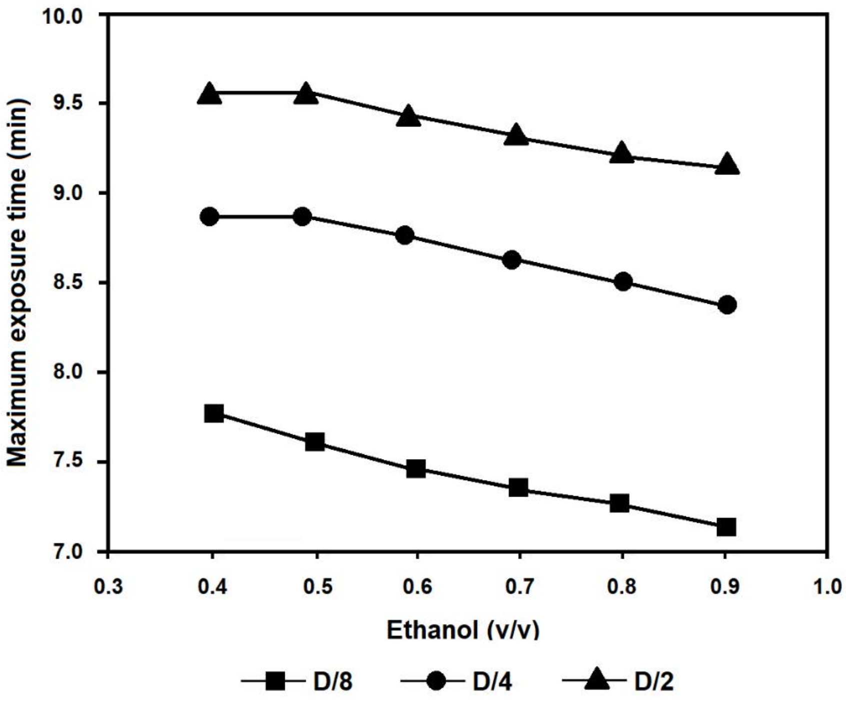

Figure 9. *Exposition limits in the function of dilution.*

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