Energy Conversion and Management xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Energy Conversion and Management

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

# Pollutant emission of gaseous and liquid aqueous bioethanol combustion in swirl burners

Attila Kun-Balog, Krisztián Sztankó, Viktor Józsa *

*Department of Energy Engineering, Budapest University of Technology and Economics, Műegyetem rkp. 3-9., H-1111 Budapest, Hungary*

ARTICLE INFO

*Article history:*
Available online xxxx

*Keywords:*
Bioethanol distillation
Aqueous ethanol
Pollutant emission
Swirl burner
Emission standard
Turbulent combustion

ABSTRACT

Hydrous ethanol is produced to the largest extent among all renewable liquid fuels. The utilization of aqueous ethanol, however, seems to be a more economical solution due to considerable savings on the production costs while the combustion performance is affected slightly. In the present paper, the energy balance of aqueous bioethanol distillation was analyzed using a 12% ethanol-water solution by volume as feed. The results showed that the distillation energy-to-lower heating value ratio of 92–52% solutions are only 0.394 of that of hydrous ethanol. Combustion tests were performed at 15 kW combustion power and an air-to-fuel equivalence ratio of 1.17, utilizing 96–50% ethanol-water solutions by volume injected in both gaseous and liquid form. From a pollutant emissions perspective, all the tested alcohols are in line with the present Hungarian standard. Considering the upcoming regulations of 2018, 90–50% liquid alcohols and 80–50% evaporated alcohols already fulfill the stricter limitations.



## 1. Introduction

The greatest technological challenge of the 21st century is to reach sustainability, which is encumbered by our continuously growing energy demand. Since 86% of utilized energy currently originates from fossil fuels [1], there is high pressure on combustion engineers to increase the combustion efficiency of heat engines and lower their pollutant emissions. Due to the lack of viable alternative, liquid fuels seem poised to dominate for the foreseeable future, especially in the transportation sector [2]. Consequently, the investigation of potential renewable liquid fuels is highly relevant [3]. Among them, hydrous bioethanol was first utilized on a large scale in Brazil. Since its introduction in the 1980s, it is still produced at the largest volume of all renewable liquid fuels. Based on this fact, Cséfalvay et al. suggested the use of an ethanol equivalent for renewable energy technology calculations [4]. There is no doubt that it is agriculturally impossible to cover our entire energy demand using bioethanol; however, it seems likely that this fuel will retain its dominant position in the renewable energy mix in the future, as confirmed by, e.g., Bergthorson and Thomson [3] and Thangavelu et al. [5]. Ethanol utilization in internal combustion engines has received high scientific focus. For example, Costa and Sodré compared hydrous ethanol with a gasoline-ethanol mixture [6], Agarwal reviewed the application of biofuels in internal combustion engines [7], and Mack et al. [8] and Munsin et al. [9] investigated the utilization of aqueous ethanol from 0 to 40 V/V% water content. As a contrast, the literature on steady ethanol combustion is highly limited, as noted by, e.g., Breaux and Acharya [10], Sallevelt et al. [11], and Rahman et al. [12]. Nevertheless, bioethanol utilization is also relevant in the field of gas turbines, industrial boilers, and furnaces, where steady combustion takes place. Consequently, the present study aims to investigate steady turbulent aqueous ethanol combustion from the perspective of pollutant emission.

The energy balance of anhydrous ethanol production was investigated by, e.g., Pimentel [13] and Shapouri et al. [14], who concluded that crop type and climate strongly affect the product of fermentation. It was a common point, however, that the energy requirements for the distillation and dehydration processes represent the majority of the energy cost of production. Therefore, if a less concentrated ethanol-water solution is suitable for combustion purposes, the overall energy balance improves, thus ensuring a smaller ecological footprint, as recently confirmed by Saffy et al. [15]. Hence, the process of bioethanol production is modeled in addition to the combustion tests to provide an overview of its utilization.

Gasoline-ethanol blends (often referred to as gasohol) are used in a large volume in internal combustion engines in Brazil. Consequently, the available literature data is vast in this field. With higher ethanol concentration in the gasohol, the nitrogen oxides

* Corresponding author.
*E-mail addresses:* kunbalog@energia.bme.hu (A. Kun-Balog), jozsa@energia.bme.hu (K. Sztankó), sztanko@energia.bme.hu (V. Józsa).

http://dx.doi.org/10.1016/j.enconman.2017.03.064
0196-8904/

**Nomenclature**

| | |
|---|---|
| *ALR* | air-to-liquid mass flow ratio [–] |
| $d_0$ | initial diameter of the liquid jet [m] |
| *E* | pollutant emission (concentration) [mg/m$^3$] |
| $G_x$ | axial thrust [N] |
| $G_\varphi$ | axial flux of angular momentum [Nm] |
| $H_0$ | ambient humidity [g $H_2O$/g air] |
| *LHV* | lower heating value [MJ/kg] |
| $\dot{m}_A$ | air mass flow rate [kg/h] |
| $\dot{m}_F$ | fuel mass flow rate [kg/h] |
| *MFR* | momentum flux ratio [–] |
| *N* | number of plates [unit] |
| $N_F$ | number of fed plates [unit] |
| *Oh* | Ohnesorge number [–] |
| $p_0$ | ambient pressure [kPa] |
| *R* | inner radius of the burner [m] |
| *Re* | Reynolds number [–] |
| *S* | swirl number [–] |
| *SMD* | Sauter mean diameter [μm] |
| $T_0$ | ambient temperature [K] |
| *w* | velocity [m/s] |
| *We* | Weber number [–] |
| $\lambda$ | air-to-fuel equivalence ratio [–] |
| $\mu$ | dynamic viscosity [Pa s] |
| $\rho$ | density [kg/m$^3$] |
| $\sigma$ | surface tension [N/m] |

*Subscripts*

| | |
|---|---|
| *A* | air |
| *L* | liquid |
| *R* | relative |

($NO_X$) emissions increase, while the carbon monoxide (CO) and total hydrocarbon (THC) emissions decrease, as confirmed by Costa and Sodré [6] and reviewed by Agarwal [7] and Anderson [16]. When aqueous ethanol is blended with gasoline, however, as investigated by Chen et al. [17] and Lanzanova et al. [18], the increased water content leads to a reduced adiabatic flame temperature, hence lower $NO_X$ emission. In parallel, the CO concentration stagnates and the THC emission increases, as measured by Lanzanova et al. [18] and Gupta et al. [19]. Regarding aqueous ethanol utilization in compression ignition engines, a clear trend is not observable, and pollutant emissions are dependent on the operation parameters and the fuel concentration (for more information, see the experimental results of Mack et al. [8] and Ambrós et al. [20]). Consequently, the results that are valid for internal combustion engines must be reviewed prior to their application in steady combustion devices.

Sallevelt et al. [11] analyzed the operation of an OP16 gas turbine combustion chamber experimentally and numerically under atmospheric conditions. Comparing diesel oil and ethanol combustion showed that the latter fuel resulted in a halved $NO_X$ emission, while the CO concentration remained similar. Lupandin et al. [21] investigated the pollutant emissions of various biofuels in an OGT2500 gas turbine. The measured $NO_X$ emission was 60 and 101 ppm in the case of hydrous ethanol and diesel oil combustion, respectively. The corresponding CO emissions were 1 and 14.8 ppm, respectively. Moliere et al. [22] performed an emission analysis with a GE 6B gas turbine utilizing naphtha-hydrous ethanol blends. Compared to the operation on pure naphtha, the $NO_X$ emission continuously decreased by ethanol addition; emissions were reduced up to 62% in the case of pure hydrous ethanol combustion. The CO and THC emissions were negligible in all these cases. The reduced $NO_X$ emission of ethanol combustion compared to that of diesel oil and natural gas combustion in a gas turbine is also confirmed by the numerical calculations of Alfaro-Ayala et al. [23]. In the case of a gas turbine, the ethanol-water solution can be injected after the compressor to increase the air humidity and serve as fuel, increasing the cycle efficiency [24]. Prior to the intake of a gas turbine, hydrous ethanol can reduce the inlet temperature and increase the cycle efficiency [25]. As for meso-scale steady combustion, Gan et al. investigated the feasibility and CO emission of two burners [26]. They showed that the efficiency of the spray combustion could be increased by 2% by using a ring electrode after the fuel injector to provide a more even fuel-air mixture at the flame front. The measurements of Asfar and Hamed [27] showed that slightly diluting diesel oil or kerosene with ethanol results in reduced pollutant emissions, reaching the optimum solution at 10 V/V% ethanol content.

Breaux and Acharya [10] investigated an atmospheric combustion test rig similar to that currently used. The researchers measured the $NO_X$, $O_2$, and $CO_2$ concentration of the flue gas versus the equivalence ratio utilizing ethanol-water solutions ranging from 100–65 V/V%. The $NO_X$ emission decreased as the water content of the fuel increased. They concluded an 80 V/V% solution is recommended due to the significant savings in production costs combined with the slight effect on the combustion properties. In the remainder of the paper, due to its frequent occurrence, EtX notes the X V/V% ethanol and 100-X V/V% water solution.

A fundamental study was conducted by Rahman et al. [12] to investigate the flame propagation properties of aqueous ethanol in a constant volume chamber. Their measurements and calculations lead to the conclusion that Et100–Et80 are characterized by similar burning velocities under rich conditions. In the case of Et90 and Et80, the burning velocity exceeded that of Et100 in the case of lean mixtures. They noted that their calculations did not confirm this finding. Their explanation is that they used an Nd:YAG laser for ignition, which excites the $H_2O$ molecules to a greater extent than the ethanol, resulting in a faster ignition.

The aim of the present study is to analyze and compare the pollutant emissions of various aqueous ethanol solutions in liquid and gaseous forms. Considering that hot exhaust gasses can be used for evaporating the ethanol and injecting it in gaseous form to the combustion chamber, the evaporation process may require no external energy in a heat engine application. This finding is the source of the novelty of the present study since there is no available data on the steady combustion of vaporized aqueous ethanol according to the best knowledge of the authors. The vaporization of liquid fuels prior to the combustion chamber is known to lower the pollutant emissions since the temperature field is more even compared to liquid fuel combustion [28].

## 2. Materials and methods

In the present section, the modeling of ethanol production is first introduced in the view of the available literature data. Then, the governing parameters of atomization and swirl combustion are discussed, which is followed by the detailed introduction of the used test rig and the instrumentation.