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The effect of elevated water content on swirl-stabilized ethanol/air flames

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HIGHLIGHTS

- ▶ Differing water content in ethanol was evaluated for its combustion properties.
- ▶ Up to 20% water does not adversely impact the heat output or exit major species.
- ▶ The addition of water re-distributes the heat release and high temperature zones.
- ▶ NO_x levels are reduced with water addition.

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ABSTRACT

Ethanol is currently being considered as a potential alternative to traditional fuels. This study seeks to validate the use of hydrous ethanol in lieu of fossil fuels or anhydrous ethanol in order to reduce the production cost associated with ethanol. Experiments are conducted in a swirl-stabilized combustor, representative of a gas turbine and hydrous ethanol ranging from 0% to 40% water by volume are tested. A stable flame was achieved for fuels up to 35% water and the Lean Blow Out limit was determined for these fuels. Fuels ranging from 0% to 20% water were tested in greater detail which included thermal mapping of the flame, exhaust temperature measurements, exhaust NO_x, CO_2, and O_2 measurement, as well as CH^* and OH^* imaging of the flame. Equivalence ratio within the combustor was varied to include 0.6, 0.8, 1.0 and 1.1, representing extremely lean, lean, stoichiometric, and rich test conditions, respectively. Results revealed that the exhaust heat rate, combustion efficiency, and combustor thermal efficiency were not affected negatively by elevated water content up to 20%. However, the flame temperature did generally decrease as a result of water addition, particularly in the lower flame region. CH^*/OH^* emissions in the lower-flame region were also appreciably reduced due to the parasitic heat load of water vaporization and local quenching in the lower parts of the flame. The practical consequence of burning hydrous fuel was reduced exhaust temperature. Reduced peak temperatures lead to reductions of exhaust NO_x at all test conditions. This study indicates that hydrous ethanol with up to 20% water can potentially be used in lieu of the more expensive anhydrous ethanol for combustion applications.

1. Introduction

As global demand for hydrocarbon fuel continues to rise and available reserves of fossil fuels decrease, significant attention is being given to the development of renewable hydrocarbon fuel sources. This includes the development of bio-alcohol fuels such as ethanol. A number of studies have been performed to evaluate the feasibility of ethanol as an alternative fuel for operating internal combustion (IC) engines [1–3]. More recently, the viability of bio-fuels, including ethanol, has been explored in turbine engines both for power generation and aircraft propulsion [4]. Ethanol can replace light distillates such as gasoline and some middle distillates such as kerosene without significant changes to existing equipment or infrastructure. Blends of ethanol and conventional fuels have also been tested and have shown some promise as potential fuels [5].

The most well-known drawback of ethanol as a fuel is its relatively low heating value when compared to traditional hydrocarbon fuels. The Lower Heating Value (LHV) of pure ethanol is 21.3 MJ/L compared to a LHV of 34.9 MJ/L for Jet A fuel and 33 MJ/L for gasoline [1,4]. Therefore, in order to be competitive in terms of price per unit of energy delivered production costs

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Abbreviations: LBO, Lean Blow Out; ER, equivalence ratio; GC, Gas Chromatograph; IC, internal combustion; ICCD, Intensified Charge Coupled Device; NASA, National Aeronautics and Space Administration; CEA, Chemical Equilibrium with Classifications; DAQ, Data Acquisition System; UV, Ultra Violet; LHV, Lower Heating Value; NPT, National Pipe Thread.

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for ethanol need to be substantially lower than those of standard hydrocarbon fuel. This is currently not the case because water removal is a significant cost in anhydrous ethanol production. Two approaches that are being investigated for addressing the energy/cost issue are either to boost the volumetric energy density of the fuel through the use of energetic fuel additives [6,7] or to explore the use of hydrous ethanol so that production costs are minimized. The latter approach is explored here.

The ethanol production process includes distillation and more complicated methods such as molecular sieves to remove water from the fuel. At ethanol concentrations greater than 95.57% ethanol, or 192 proof (E95.5/W4.5), hydrous ethanol is an azeotropic mixture. Because of the azeotropic nature of this mixture a significant additional investment in energy and capital is required to achieve anhydrous fuel [3]. Additional economic gains can be achieved from reduced distillation costs if the final ethanol concentration is below the azeotropic limit [8]. These gains will potentially be greater than the losses resulting from increased transportation costs [9]. It has been claimed that the production and efficient use of 70 proof ethanol (E35/W65) would result in a 34% increase in the net energy gain when compared to anhydrous ethanol [2] due to the reduction in the water separation cost from 37% of the total production cost for anhydrous ethanol down to 3% of the total production cost while producing E35/W65 [2]. The use of 70 proof ethanol, which is 65% water by volume, is an unlikely candidate for combustion applications because of reduced temperatures and water-quenching effects. However, it is possible to find a more moderate proof of hydrous ethanol that will result in reasonable functionality while still substantially reducing the cost of ethanol production. For example, the use of an E80/W20 would require approximately a quarter of the distillation energy required to achieve E96/W14 [9].

Lower proof ethanol possesses fewer ethanol molecules per unit volume than pure ethanol because ethanol molecules are displaced by an increasing amount of water. Correspondingly, the LHV, both on a volumetric and gravimetric basis, of the fuel is reduced with increasing water content. Therefore the use of a lower-proof ethanol fuel results in the consumption of larger volumes of fuel to produce the same amount of energy, but may be economically advantageous.

Previous studies have considered the use of wet ethanol in IC engines [2,3,10] or have considered the burning velocity of hydrous ethanol at concentrations greater than 170 proof (E85/W15) [11]. Limited work, however, has been done concerning the use of wet ethanol in a swirl-stabilized continuous flame combustor. Information provided from such a study will be particularly relevant to the use of wet ethanol in turbine and industrial burner applications.

It is known that increasing water content of the fuel will decrease the adiabatic flame temperature of the combustion reaction. Adiabatic Flame Temperatures for perfectly mixed reactions were calculated using NASA CEA code [12] for various equivalence ratios and water concentrations and is presented in Fig. 1. This reduction in temperature will undoubtedly result in a reduction in NO_x formation by reducing thermal NO_x. This decrease in adiabatic flame temperature is accompanied by an increase in latent heat of vaporization. Water requires more heat to evaporate than ethanol and as a result the amount of heat required to vaporize a high water content fuel is greater. These characteristics of hydrous ethanol may have adverse effects on fuel vaporization and combustion efficiency. The operational limits of the combustor, in terms of equivalence ratio (ER), may be affected adversely by low alcohol proof.

This paper seeks to provide a detailed view of how increasing water content effects flame structure, flame stability, flame temperature, heat release, and exhaust NO_x, CO_2, and O_2 concentration. Two preliminary non-archival studies using this experimental apparatus have been presented previously. The first paper focused on flame temperature and LBO measurements [19] while the second paper focused on chemiluminescence diagnostics [20]. This archival study is unique in combining the results from previous studies, along with additional exhaust gas measurements, to make substantive conclusions on the effect of water addition on ethanol. This study represents the only comprehensive study of a hydrous ethanol flame in a swirl-stabilized combustor. It is pertinent to understand how elevated water content affects the operational limits and performance of the swirl-stabilized combustor. This information is particularly relevant in evaluating hydrous fuel as a candidate in fuel flexible gas turbine operation or fuel flexible industrial burners.

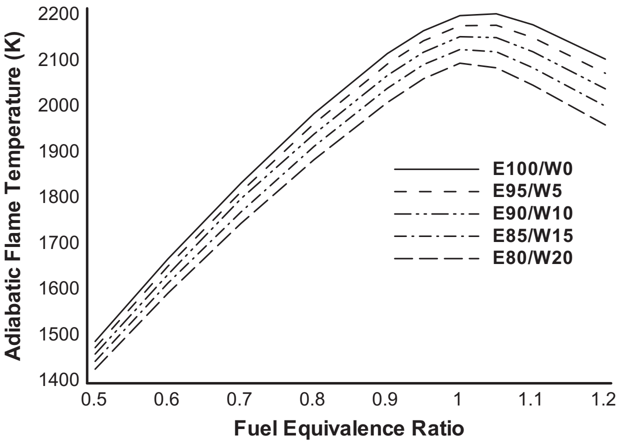

Fig. 1. Adiabatic flame temperature of hydrous ethanol, calculated using NASA CEA code [12].

2. Materials and method

2.1. Experimental setup

The experimental setup, shown in Fig. 2, uses a vertically oriented swirl-stabilized combustor that is circular in cross section. The combustor exit is unrestricted, allowing for atmospheric pressure, and the inlet is a dump diffuser with an area ratio of 35.73. The combustor shell inside diameter is 27.3 cm with a single fuel atomizer located at the center of the dump plane. For all experiments the air flow rate was held constant at 18.88 L/s. This ensures that the air flow velocity field within the combustor does not vary between tests. Axial vane swirlers were utilized in conjunction with the dump to stabilize the flame and induce hot gas recirculation. Two swirlers are situated at locations 2.54 and 19.05 cm upstream of the dump plane. Each of these swirlers has eight 45° vanes, resulting in a geometric swirl number of 0.755. Absolute air velocity as it exits the swirler is calculated as 22.3 m/s, with tangential and axial components both equal to 15.8 m/s. Turbulence intensity of the non-reacting air flow was measured using an IFA-300 hot-wire anemometer system, revealing a minimum turbulence intensity of 25% at all radial locations for axial locations closer to the dump plane than $x/D = 0.60$.

Fuel is supplied to the center of the combustor through a lone single-point Parker–Hannifin pressure swirl atomizer with a hollow cone spray pattern. The nozzle tip is situated 1.27 cm below the dump plane. This location was chosen to enhance flame anchoring through the use of swirl and provide a more consistent flame structure. The tests span a wide range of fuel flow rates, varying from 0.123 to 0.282 L/min. This is necessary to achieve the wide range of equivalence ratios desired with each fuel composition. In order to achieve this range of fuel flow rates nozzles were interchanged throughout the study. All nozzles follow the same