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Effect of naphthalene addition to ethanol in distributed combustion

Joseph S. Feser[a], Ghada Bassioni[a,b], Ashwani K. Gupta[a,*]

[a] Mechanical Engineering Department, University of Maryland, College Park, MD 20742, USA
[b] Chemistry Department, Faculty of Engineering, Ain Shams University, P.O. Box 11517, Cairo, Egypt

HIGHLIGHTS

- Naphthalene ethanol mixtures are tested under colorless distributed combustion.
- Examination of naphthalene concentration in ethanol at multiple equivalence ratios.
- NO and CO emissions are reduced under certain conditions of CDC.
- Naphthalene addition increases the heat content of ethanol fuel.

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ABSTRACT

Naphthalene as a fuel additive to ethanol was examined in a swirl combustor with the objective to obtain efficient burning and ultra-low emissions using different heating value fuels. Naphthalene is a polyaromatic compound often regarded as a waste fuel that results in high levels of pollutants emission. The effectiveness of naphthalene as a fuel additive to ethanol on NO and CO emissions and stability was determined. The naphthalene concentration was varied from 0 to 0.4 mol/L in ethanol, corresponding to a heating value increase of 8.8% on a volumetric basis (or 5.7% on mass basis). Emissions data were reported for Colorless Distributed Combustion (CDC) using N_2/CO_2 dilution, at equivalence ratios (Φ) of 0.9 and 0.7. The data under normal fuel–air combustion conditions also reported, clearly showing the benefits of CDC. NO and CO emission below 1 and 6 ppm, respectively, were achieved under CDC conditions for each of the naphthalene-ethanol fuels examined. The results at both the equivalence ratios showed lower NO emission with increase in naphthalene concentration, which provided higher heating value fuel mixture. The CO emission was also low and remained negligibly unchanged with change in naphthalene concentration and equivalence ratio. The results show the use of naphthalene addition to ethanol for increased heating value fuel with ultra-low emissions and higher stability under distributed combustion conditions.

1. Introduction

With continuously rising energy demand worldwide, concerns over the depletion of fossil fuel reserves and increasingly stringent emissions standards, engineers have been challenged to develop novel combustion techniques to enhance combustor performance, reduce emissions, and also utilize the available abundant renewable fuels. One such novel technique which provides near zero emissions and fuel flexibility is Colorless Distributed Combustion (CDC). CDC performance has been examined in a variety of combustor configurations, thermal intensities and fuels at various equivalence ratios with the goal of achieving near zero pollutants emission along with increased performance [1–4]. Fuel flexibility has been examined for gaseous as well as liquid fuels, including liquid biofuels [4,5].

The CDC was based on some of the design principles for high temperature air combustion (HiTAC) [6]. By preheating low oxygen concentration air to very high temperatures so that combustion gases are only 50–100 °C above the preheated air temperatures prior to ignition, HiTAC technology demonstrated ultra-low emissions, uniform thermal field, low noise, as well as energy savings for near atmospheric pressure furnace applications [6]. CDC also uses decreased oxygen concentrations in the fresh mixture stream; however, this method relies on internal entrainment of hot reactive species inside the combustor in order to provide a volume distributed reaction regime, and is primarily aimed for high intensity gas turbine combustion applications. CDC is named as such because of the nearly invisible (colorless) flame produced when firing under the distributed reaction regime.

CDC is reported to show ultra-low pollutants emissions using

* Corresponding author.
E-mail address: akgupta@umd.edu (A.K. Gupta).

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biofuels compared to fossil liquid fuels [5]. Therefore, focusing on CDC for biofuels would be increasingly beneficial, considering fuel additives could enhance even further effective biofuel combustion. Fuel additives have been employed in biofuels for numerous applications, such as, ignition promoters, stability enhancers, and emissions reducers [7]. Under distributed combustion conditions, the emissions were substantially reduced by some 95% to result in NOx emissions of less than 2 ppm with minimal impact on CO emission from both JP-8 and ethanol fuels at an equivalence ratio of 0.9. Lower equivalence ratios demonstrated even lower emissions. Combining the data obtained with liquid fuels with those from gaseous fuels revealed that, regardless of the fuel used, the oxygen concentration at which CDC prevailed can be predicted based on mixture temperature within a range of 0.75% [8]. Naphthalene, well known for its use as the main ingredient in old moth balls, has been used as a fuel additive in order to reduce engine deposits [9], as well as increase fuel performance [10,11]. However, there is currently a very limited amount of relevant literature detailing the effects of naphthalene addition in fuels, on performance or emissions. There are no studies on the use of naphthalene under distributed combustion condition. In this study, the use of naphthalene as a fuel additive in ethanol was examined with a focus on providing data for naphthalene undergoing combustion and its subsequent effect on emissions and combustor performance. This provided useful insights on the use of naphthalene in the CDC design for stationary gas turbine combustion applications.

2. Materials and methods

Naphthalene (99%, Acros Organics) and ethanol (200 Proof ACS/USP Grade, Pharmco-Aaper) were used as purchased without further purification. 0.1, 0.3 and 0.4 M solutions of naphthalene in ethanol were prepared at room temperature and compared to pure ethanol. The densities of these solutions were calculated using interpolation of the published data for naphthalene-ethanol mixtures [12]. The heating value of the mixture was calculated by multiplying heating values of the fuel constituent by the respective mole fraction, assuming complete combustion.

The combustion experiments were performed using a swirl burner shown in Fig. 1. Details of this burner can be found elsewhere [13]. A schematic diagram of the experimental setup is given in Fig. 2. The air and nitrogen flow rates were controlled by laminar flow controllers with accuracies of ± 0.8% of the reading and ± 0.2% of full scale. Carbon dioxide was controlled using a gravimetric flow controller with an accuracy of 1.5% of full scale. The liquid fuel was supplied using a liquid handling pump with an accuracy of ± < 0.5%. Heating tape was used to heat and vaporize the fuel into gaseous form while retaining the fuel chemical composition.

In order to support CDC condition, spatial distribution of OH^* chemiluminescence signal was investigated [14]. An ICCD (intensified charged-coupled device) camera coupled with a narrow band filter for OH^* chemiluminescence detection was used with UV interference filter centered at 307 nm, FWHM ± 10 nm. The camera was set to a gain of 0 and an exposure time of 70 ms.

The pollutants emission as well as the combustion products speciation were continuously sampled at the outlet of the burner and then passed through a desiccant to remove any moisture. NO was measured using an NO-NO_x chemiluminescent gas analyzer while CO was measured using a non-dispersive infrared method. The O_2 concentration was measured using the galvanic cell method. The O_2 measurement was used for correcting the NO and CO emissions to the standard 15% oxygen concentration used for gas turbine emissions.

Table 1 summarizes the experimental conditions reported in this study. Naphthalene content in ethanol was varied from 0.1 mol/L to 0.4 mol/L. Although the solubility limit of Naphthalene in ethanol is just over 0.6 mol/L of ethanol at 298 K [15], concentrations of naphthalene in ethanol higher than 0.4 mol/L were practically not

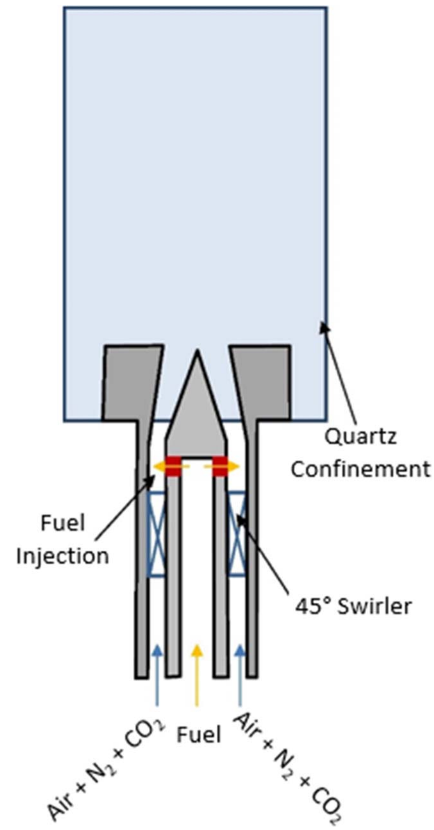

Fig. 1. Schematic of the experimental test combustor facility.

achievable. Due to extensive required mixing time and practically of having the fuel always stored at above 298 K, the naphthalene concentration were limited to 0.4 mol/L. For all conditions the inlet fuel temperature was maintained at 500 K (which is above the boiling points of both ethanol: 351 K and Naphthalene: 491 K) in order to ensure the fuel mixture examined in the burner was the same as prepared. The results are reported at two equivalence ratios of $\Phi = 0.9$ and 0.7. The equivalence ratio is a non-dimensional parameter, defined as the ratio of actual fuel-air ratio (FAR) to stoichiometric fuel-air ratio (FAR_{st}), i.e., $\Phi = \frac{FAR}{FAR_{st}}$. The particular equivalence ratios examined are higher than that used in todays' gas turbine engines. They are useful for the design of future generation CDC gas turbines that offer higher thermodynamic efficiency and increased performance. In gas turbine combustion excess air is used so that the turbine blades can handle the high temperatures and also mitigate the hot spot zones to minimize the amount of NOx, CO, unburnt hydrocarbons formed. An equivalence ratio of 0.9 was chosen due to excessive NO_x formation under normal conditions at such a high equivalence ratios. Reduction of NOx at such high equivalence rations using higher energy density fuels is of great importance for demonstrated ability of CDC for practical deployment in gas turbines. Additionally, carbon monoxide, unburnt hydrocarbons, and carbon/soot emissions are reduced under distributed combustion conditions [1,4,6]. Combustion of aromatics and polyaromatic compounds, such as naphthalene, are of concern as they often give higher pollutants emission, including soot [6]. Although hydrocarbon emission was not investigated in this study, unburnt hydrocarbon emission has been shown to be provide similar trend to CO [16]. Air, nitrogen, and carbon dioxide, however were supplied at 300 K. Nitrogen and carbon dioxide were supplied using a 90:10 N_2 to CO_2 mixture in order to reduce the oxygen concentration.