



Utilizing preferential vaporization to enhance the stability of spray combustion for high water content fuels



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ABSTRACT

In a previous study on the stability of spray combustion for mixtures of alcohols (ethanol or 1-propanol) and water, the feasibility of burning fuels heavily diluted with water was demonstrated. In that study it was found that the preferential vaporization of alcohols in water can significantly enhance flame stability. Due to their high volatility and high activity coefficient in aqueous solution, the alcohols quickly evaporate from the droplets and generate a concentrated fuel vapor at the base of the jet. Therefore, a flame can be ignited and stabilize even though the water content of the fuel is quite high (up to 90 wt%) (Yi and Axelbaum, 2013). In this study, we develop a procedure for selecting chemical fuels showing strong preferential vaporization in water. *t*-Butanol was identified as an excellent candidate based on its physical and chemical properties, including activity coefficient, vapor pressure, heat of vaporization and heat of combustion. Flame stability was evaluated for aqueous solutions of both ethanol and *t*-butanol using a spray burner where the extent of swirl was adjustable. Under both high and low swirl intensity, the flame stability of *t*-butanol aqueous solutions was better than that of ethanol. The characteristic time for fuel release from a droplet was modeled for both ethanol and *t*-butanol. The time to release 99% of the fuel from the droplet for *t*-butanol is over 70% shorter compared to that for ethanol, which supports the improved flame stability observed for *t*-butanol in the experiments.

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1. Introduction

In our previous study, we demonstrated the feasibility of combusting fuels heavily diluted with water [1]. Direct combustion of high water content fuels provides an approach to extract chemical energy from fuels that intrinsically have high moisture content. Compared to traditional approaches, this approach has the advantage of avoiding the energy intensive dewatering process, making the overall energy efficiency of the process higher. Furthermore, if used in pressurized systems, the latent heat used to evaporate the water can be recovered and utilized. In addition, if oxygen is used as the oxidizer, it allows for efficient carbon capture. Recently, Clean Energy Systems, Inc. (CES, Sacramento, CA) is utilizing direct steam generation with a natural gas burner to generate power while enabling carbon capture [2].

Many high water content fuels exist in nature, either in their raw state or at some point during their processing. For example, microalgae naturally contain a large percentage of water when they grow. While microalgae have become a promising feedstock for biofuel production due to their fast growth rate and high oil content [3,4], the water content in the microalgae culture is above

99 wt%. To achieve high recovery efficiency during oil extraction, it is necessary to reduce the water content to as low as 1 wt% after dewatering [5]. The processes involved in reducing the water content to that level accounts for 20–30% of the total production cost [6]. This is one of the primary reasons that biofuel production from microalgae is not presently economical [7,8].

Fine coal is another example of a fuel with a high water content, but in this case the water comes from processing. After mining, coal is crushed and washed. The coal particles larger than 500 μm are screened out and fine coal is left [9]. Fine coal is commonly upgraded by column flotation, which produces clean coal slurry containing about 80 wt% water. Due to the lack of a cost effective technology for moisture removal, many coal producers discard their fine coal streams. In U.S. alone, there are approximately 2 billion tons of fine coal discharged in abandoned ponds and 500–800 million tons of that in active ponds. Every year, U.S. coal producers discard about 30–40 million tons of fresh fine coal to active ponds [10]. As a reference, the U.S. coal consumption for electric power was 885 million tons in 2010 [11].

Bioethanol is also a fuel that experiences high water content during processing. Normally, the water content in the water-based broth reaches more than 90 wt% during the fermentation step, since at higher ethanol concentrations inhibition would significantly slow down production. To obtain anhydrous ethanol, the

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broth has to go through distillation and dehydration [12,13]. The energy consumed in distillation and dehydration accounts for 37% of the total energy in ethanol and coproducts [14].

Recognizing the high cost of dewatering in bioethanol production, some studies have been conducted on combustion of “wet” ethanol. In Refs. [15,16], the use of wet ethanol in HCCI engines was evaluated and stable operation was obtained for ethanol containing up to 46 wt% water. Breaux and Acharya conducted experiments in a swirl-stabilized combustor and a stable flame was achieved for ethanol with a water content up to 41 wt% [17]. Since they found that the range of operability for wet ethanol is limited, they characterized the flame burning ethanol with a water content less than 24 wt%. The above studies were performed under air-fire conditions.

Yi and Axelbaum studied the flame stability of ethanol/water mixtures and 1-propanol/water mixtures in a swirl-stabilized combustor [1]. Experiments were conducted in oxygen-enriched air as well as air. This study found that preferential vaporization of the alcohol is an important factor in stabilizing spray flames of alcohols heavily diluted with water. The alcohols quickly release from the spray and generate concentrated fuel vapor at the base of the jet. Therefore, a flame can be ignited and stabilize even though the water content in the liquid is very high. They observed self-sustained combustion of fuel with 75 wt% water when burning in air and 90 wt% water when burning in 60% O₂.

In this study, we develop a procedure for selecting chemical fuels showing strong preferential vaporization in water. *t*-Butanol, even though not naturally abundant, was identified as an excellent candidate, based on its physical and chemical properties, including activity coefficient, vapor pressure, heat of vaporization and heat of combustion. Flame stability was evaluated for aqueous solutions of *t*-butanol using a spray burner and the results are compared with that for ethanol aqueous solutions. In addition to being useful for gaining a fundamental understanding of combustion of high-water content fuels, a chemical fuel such as *t*-butanol, which shows strong preferential vaporization in water, could potentially be used as an additive in less volatile fuels like slurries of fine coal or algae, to support direct combustion.

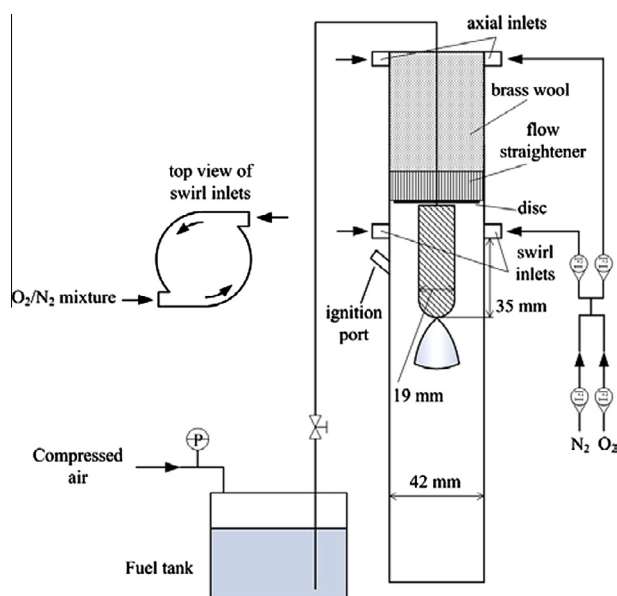


Fig. 1. Experimental setup for spray combustion stability studies.

2. Experimental

The experimental setup is shown in Fig. 1. The burner used in this study is a swirl-stabilized burner, which was upgraded from one used in our previous work [1]. The swirl flow is introduced by two swirl inlets, which are tangential to the inner wall. In order to control the swirl intensity, an axial flow has been added to the burner at the top. The main oxidizer stream is split into an axial flow and a swirl flow and the proportions of each can be controlled. Generally, the higher the proportion of swirl flow the stronger the swirl intensity. The inner diameter of the tubes, both for the swirl and axial inlets, is 4.6 mm. Compressed air was used to generate a head pressure that was used to pump the mixtures of water and the chemical fuels into the nozzle, which was located on the axis of a quartz chamber. The spray nozzle and operating pressure for the spray were the same as in our previous study (Newton Tool & Manufacturing Co., Inc., model number 0.5NS30 and 3.4 atm pressure) [1]. Both the liquid mixture and oxidizer were introduced at room temperature, 20 °C, and the experiments were run at atmospheric pressure. In each experiment, the flame was ignited by a pilot flame from ignition port. In order to reproduce the experiments of our previous study under 100% swirl conditions, a 38 mm disc was placed after the flow straightener. The disc avoids back-flow through the honeycomb under very strong swirl conditions.

Flame stability was characterized by the blow-off limit (i.e. the lowest O₂ concentration where a flame could exist under a given oxidizer flow rate), as in our previous study [1]. For experiments under 100% swirl flow condition, the O₂ concentration in the oxidizer stream was reduced in small decrements by increasing the N₂ flow rate until the flame extinguished. All gas flow rates were then recorded and the O₂ mole fraction at the limit was calculated. However, the experimental procedure was different when the flow was a combination of axial and swirl. In this case, the flow rates for the O₂ and N₂ streams were fixed such that the O₂ concentration and the total flow of the oxidizer were fixed for each run. The spray was ignited under 100% swirl condition. Then, the flow through the axial was increased until the target proportion of axial flow was reached. The O₂ concentration was gradually reduced until the blow-off limit was identified. The limits reported are average values of three experimental results at each data point, and the standard deviation is within one percentage point.

3. Results and discussions

3.1. Selection of fuel

In our previous study [1], ethanol and 1-propanol were used as fuels to study flame stability for alcohols heavily diluted with water. From the results of both experiments and modeling, it was concluded that preferential vaporization of the alcohol played a significant role in flame stabilization. The rapid evaporation of fuel from the droplets causes the local fuel vapor fraction in the vicinity of the nozzle to be much higher than its corresponding fraction in the liquid. This phenomenon allows for stable combustion of fuel–water mixtures with a water content as high as 75 wt% when burning in air and 90 wt% when burning in 60% O₂. The activity coefficient of alcohol in water was found to be particularly important for preferential vaporization when the water content is high.

Based on this understanding, we searched for chemicals that show an even stronger preferential vaporization than ethanol and 1-propanol. Utilizing these chemicals in high water content systems could potentially enhance flame stability. The search was limited to water-soluble chemicals. The selection was based on an understanding of the mechanisms controlling preferential

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