



# Spray breakup and structure of spray flames for low-volatility wet fuels



José E. Madero<sup>a</sup>, Richard L. Axelbaum<sup>b,\*</sup>

<sup>a</sup> Department of Mechanical Engineering and Materials Science, Washington University in St. Louis, St. Louis, MO 63130, USA

<sup>b</sup> Department of Energy, Environmental, and Chemical Engineering, Washington University in St. Louis, St. Louis, MO 63130, USA

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## ABSTRACT

Studies of high-water-content fuels (a.k.a., wet fuels) have demonstrated that, under proper conditions, stable combustion can be achieved at very high water concentrations. Stable spray flames of wet fuels have been attained with fuel/water mixtures having stoichiometric adiabatic flame temperatures as low as 251 °C. In this study, we investigate low-volatility wet fuels, using glycerol as the fuel and ethanol as a stabilization additive. This study expands on previous work by determining the minimum amount of ethanol that needs to be added to a glycerol/water mixture to produce a stable flame and by investigating the spray dynamics and structure for these fuels, to delineate the mechanism of ignition and to understand how ethanol alters the vaporization behavior, droplet breakup, and spray dynamics. Detailed 2-D velocity, Sauter mean diameter (SMD), 2-D flux, and number concentration measurements were performed with a Phase Doppler Particle Analyzer (PDPA) in sprays of three fuel/water mixtures: (a) 30% glycerol/70% water, (b) 30% glycerol/10% ethanol/60% water, and (c) the same mixture as (b) but in a combusting spray. All percentages are by weight. Results show that the addition of ethanol to the glycerol/water mixture turns the hollow-cone spray pattern into a narrow full-cone pattern, leading to recirculation of fine droplets in the region just downstream of the nozzle, which is essential to ignition. The high concentration of fine droplets, along with the high vapor pressure and high activity coefficient of ethanol, lead to extremely rapid vaporization of ethanol in the inner recirculation zone. The combustion of the ethanol raises the temperature in this region, while the swirling flow brings heat upstream towards the nozzle, further enhancing stability. These results explain why the addition of 10% ethanol can lead to robust flames of glycerol/water mixtures that might not be expected to yield stable combustion.

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## 1. Introduction

Despite the low calorific value of high-water-content (wet) fuels, direct combustion can be used to extract energy from fuels that might otherwise be of limited value. Furthermore, such an approach would have the advantage of avoiding the energy-intensive dewatering processes. For example, dewatering can account for as much as 37% of the energy content in bioethanol [1] and 20–30% of the total production cost of biofuel from microalgae [2]. In addition, since the products of combustion would contain a considerable amount of water, a high-temperature and high-pressure stream of steam could be produced in one step rather than the traditional two-step approach involving a combustor and boiler. Thus, a simple and compact system could be utilized for applications that require high temperature steam, such as in the oil industry,

where steam is injected into oil sands to extract liquid fuels [3]. Direct combustion of wet fuels also shows promise for energy generation. Since the steam temperature would no longer be limited by heat transfer through the boiler tubes, higher temperatures than those allowed by even the most advanced boiler materials could be achieved and this can lead to a considerable increase in efficiency [4,5]. If used in pressurized systems, the latent heat used to evaporate the water could be recovered and utilized, and if oxygen is used as the oxidizer, this would allow for efficient carbon capture after the steam is condensed [6–8].

Previous studies have demonstrated the feasibility of combusting fuels containing high water content. Breaux and Acharya obtained a stable flame for 59% ethanol/41% water mixtures in a swirl-stabilized burner [9]. Stable operation in HCCI engines was demonstrated with ethanol containing up to 46% water by Mack et al. [10] and Saxena et al. [11]. Yi and Axelbaum attained self-sustained combustion of ethanol with as little as 25% ethanol when burning in air and 10% ethanol when burning in 60% O<sub>2</sub> in a swirl-stabilized burner [12].

\* Corresponding author at: One Brookings Drive, Box 1180, Brauer Hall, St. Louis, MO 63130, USA.

E-mail address: [axelbaum@wustl.edu](mailto:axelbaum@wustl.edu) (R.L. Axelbaum).

### 1.1. Preferential vaporization of wet fuels

The stoichiometric adiabatic flame temperatures of wet fuels can be quite low. For example, for a 10% ethanol/90% water mixture burning in 60% O<sub>2</sub> flame, it is 251 °C and thus, these conditions might not be expected to lead to stable burning [12]. During spray combustion, the partial pressure of fuel at the droplet surface can be estimated from Raoult's Law [13]. In addition, when an alcohol is mixed with water, a non-ideal solution is formed, leading to an activity coefficient that can be much greater than unity. A high activity coefficient can dramatically increase the extent of preferential vaporization by increasing the equilibrium fraction of fuel in the vapor phase [14]. Also, the activity coefficient of alcohol in water increases as the water fraction increases and can be as high as 5 for a mixture of 10% ethanol/90% water, implying that the vapor pressure at the surface is five times higher than it would be for an ideal mixture at the same temperature. This increase in activity coefficient can offset the reduction in fuel vaporization rate that one might expect when the fuel is diluted, and this phenomenon was found to allow for stable combustion of very dilute ethanol/water mixtures as described above [12].

In the case of fuels with low volatility relative to water, the opposite behavior occurs, wherein the water can vaporize preferentially over the fuel. Yi and Axelbaum studied oxy-combustion of glycerol/water mixtures [15]. Glycerol is a by-product of biodiesel production, with limited commercial value. Typically, it takes between 0.3 and 1 gallon of water to separate the glycerol from biodiesel, and 10–20% of the total volume of biodiesel produced is made up of glycerol [16]. As biodiesel production increases, finding uses for this by-product is becoming important in order to improve the economic viability of biodiesel. One option is to use it as a fuel for process heating or electricity generation. Direct combustion of glycerol has been achieved by heating the fuel to reduce the kinematic viscosity of the fuel so that it can be atomized, and by heating the oxidizer to overcome the high ignition temperature of glycerol [17,18]. Jian and Agrawal were able to achieve stable combustion of neat glycerol without preheating the fuel by using a novel flow-blurring liquid fuel injector in an insulated combustor [19].

Glycerol has a high boiling point (290 °C), a low vapor pressure, and an activity coefficient of nearly unity when mixed with water. Thus, when glycerol is used as a wet fuel, water vaporizes preferentially over the fuel, making it difficult to burn, and, unlike when burning pure glycerol, preheating the fuel does not aid ignition. The addition of water does, however, lower the kinematic viscosity, so atomization is not an issue as it is with neat glycerol.

In Ref. [15], stable glycerol/water flames were obtained with 60% glycerol/40% water when burned in pure oxygen, but the flame was lifted from the nozzle despite the fact that the stoichiometric adiabatic flame temperature of this flame is 2602 °C. To enhance the stability of the glycerol/water mixtures, a high volatility fuel was added to the mixture, allowing attached, robust flames to be obtained for 30% glycerol/10% ethanol/60% water mixtures in pure oxygen. That work concluded that the addition of ethanol increased the fuel vapor pressure near the nozzle, which allowed for ignition and stable combustion.

The present study expands on this previous work to better understand the mechanism by which ethanol addition to glycerol/water mixtures improves flame ignitability and stability. This is accomplished by investigating spray breakup and spray structure of glycerol/water and glycerol/ethanol/water mixtures. The former mixture represents the reference low-volatility wet fuel and the latter represents a low-volatility wet fuel wherein a high-volatility fuel is added to improve flame ignitability. Since the objective is to understand how the addition of small amounts of ethanol turns a non-ignitable mixture into one that yields a robust flame, a cold

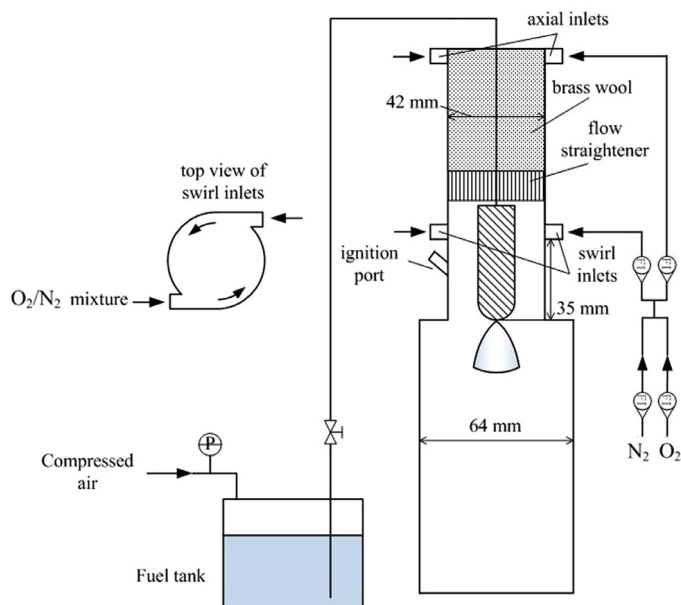


Fig. 1. Description of swirl-stabilized burner.

glycerol/water spray was studied in detail even though the spray dynamics are very different from that of a combusting spray, as this condition serves as the state that needs to be ignited before a stable flame can be reached. Breakup of the sprays was studied using high-speed video, and measurements of the 2-D velocity, Sauter mean diameter (SMD), 2-D flux, and number concentration were obtained, both with and without combustion, using a Phase Doppler Particle Analyzer (PDPA).

Numerous studies, both fundamental [20–23] and experimental [24–29], have shown that altering fluid properties such as surface tension, viscosity and specific gravity can affect both the spray breakup process and the spray cone angle, which in turn can affect the droplet size and velocity distributions. Since glycerol/water mixtures are inherently unstable, even minor changes in the spray characteristics can impact the ignition and stability of such systems. Therefore, an understanding of the effect that the additive has on spray breakup and structure, in conjunction with the effect it has on preferential vaporization, is needed before the combustion of wet fuels can be fully understood and utilized.

## 2. Experimental setup

The swirl-stabilized burner used is the same as in Ref. [15] and a schematic is shown in Fig. 1. A pressure-swirl hollow-cone nozzle with a nominal 30° angle was used (Monarch Nozzles 0.5NS30). The nozzle has a 14 mm diameter and a 0.2 mm discharge orifice. The pressure drop across the nozzle was held constant at 6.8 atm. The oxidizer flow was controlled via mass flow controllers and injected through 6.35 mm inlets. Only the swirl inlets were utilized, and both fuel and oxidizer were introduced at 25 °C for all cases studied. Ignition was achieved with the use of an ethane torch inserted through the ignition port and placed downstream of the nozzle. The torch was removed once a flame attached to the nozzle could be observed, or after a few minutes if no ignition was possible.

To determine the minimum amount of ethanol that needs to be added to a glycerol/water mixture to produce a stable flame, different glycerol/water mixtures were used and then ethanol was added in 2.5% increments until it was possible to ignite the system and obtain a stable flame. The three cases studied in detail are summarized in Table 1. The fuel tank was placed on a weighing

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