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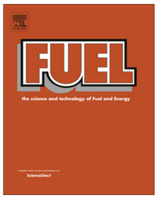

Full Length Article

Combustion characteristics of ternary fuel Blends: Pentanol, butanol and vegetable oil

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ABSTRACT

Ternary blends of pentanol, butanol and soybean oil are investigated and compared to binary blends of pentanol/soybean oil and butanol/soybean oil. Ternary blends are examined in an effort to create more intense and longer lasting puffing events and microexplosions, with the overall goal of increasing reaction rates and improving combustion of heavy bio-oils. Several blend ratios were tested for the ternary mixture. All the blends tested exhibit significant puffing events. The size of puffing event is closely linked to the amount of secondary atomization that occurs and therefore the overall shortening of reaction time. An equivolume blend of pentanol, butanol and soybean oil exhibits the most violent microexplosions and leads to the shortest reaction time. A hypothesis is suggested for the difference in combustion behavior between binary and ternary fuel blends.

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1. Introduction

Liquid fuels will have a role to play in our energy future, however transition to renewable fuels is necessary in order to mitigate contribution to climate changing anthropogenic gases. More energy efficient and cost effective renewable fuels are also required to advance the transition off of petroleum-based fuels economically. Ethanol and biodiesel have been the most common biofuels employed in combustion applications, however biodiesel requires a batch processing method of production and creates a waste product, glycerol, thus reducing the overall efficiency of its production. Alternatives to biodiesel have been examined such as simple mixing with alcohols that can be made from biomass sources, such as methanol and ethanol. However, in recent years longer chain alcohols, such as butanol and pentanol have gained attention as second-generation biofuels. These fuels have higher energy density, are more miscible with diesel and have higher boiling and flash point temperatures as compared to methanol and ethanol, making them attractive for combustion applications.

The purpose of this study was to extend the duration of ‘puffing’ that is observed in the combustion of single droplets of binary blends of vegetable oil and butanol. Puffing and microexplosive combustion behavior are well documented in the literature for fuel blends with high volatility differences [1–5]. In this study puffing events are considered to be those in which the droplet undergoes internal boiling and secondary atomization but the major portion of the droplet remains attached to the cross hairs. A microexplosion is defined as an internal boiling event that is strong enough to rip the body of the droplet apart to the point it does not stay on the cross hairs. Puffing and microexplosions lead to secondary atomization. Secondary atomization increases the surface area exposed to the reacting environment leading to higher evaporation rates and thus reaction rates of the fuel [1]. Microexplosions occur when the more volatile component evaporates from the droplet surface, leaving a high concentration of the higher boiling point fuel behind. The droplet then undergoes intense heating leading to superheating of the remaining fuel within the droplet that has a substantially lower boiling point. The lower boiling point fuel then boils causing the droplet to expand and jet secondary droplets. This is advantageous as smaller droplets in reacting sprays have been shown to lead to a more premixed prevaporized reaction, thus improving efficiency and decreasing harmful emissions such as soot and NOx [6,7].

Recent studies of pentanol have focused on blending with diesel for application in diesel engines. Campos-Fernández et al. tested longer chain alcohols up to 30% in diesel engines with diesel and found little change in engine performance. A slight decrease in engine power and an increase in brake thermal efficiency was noted [8]. Also, Li et al. tested a ternary blend of diesel, biodiesel and pentanol in a single-cylinder direct-injection diesel engine and found an obvious reduction in soot production and NOx [9]. Other fundamental studies of pentanol have focused on chemical kinetics and combustion modeling [10–12].

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The combustion of ternary blends has received little attention in the literature. However, there are a couple of studies that looked at blends of diesel, biodiesel, and ethanol. Avulapati et al. examined this ternary blend and found certain mixtures exhibited puffing and some blends led to microexplosions [13]. The study described herein, examined blends of soybean oil, pentanol and butanol. Previous studies of soybean oil and butanol showed puffing occurs for these blends; with the most violent puffing occurring for equivolume blends [14]. The goal of this study was to increase the length of time that puffing occurred and therefore of continued secondary atomization and more efficient combustion.

2. Materials and methods

2.1. Experimental facility

Experiments were conducted in a large, cubic furnace. The interior chamber of the furnace measured 25.4 × 25.4 × 25.4 cm. The furnace had two glass-viewing ports, each 6.35 cm in diameter, through which the experiment could be recorded. An IDT NR4-S2 camera connected to Motion Studio x64 software was used to record each trial through one of the viewports, with a 50 W Solar-c light box attached to provide adequate illumination. A Eurotherm 3504 PID controller was used to control the temperature within the furnace. Inside the furnace, two ceramic microfibers were set up to cross perpendicularly at the center of the chamber, upon which the droplet was suspended to run experiments. Two Type K thermocouples were situated near the intersection of the microfibers, one approximately two millimeters to the side and one 4.5 mm above. The side thermocouple, with a known bead diameter of 1.3 mm, was kept in the camera's field of view for use as a size reference. The thermocouples were connected to a National Instruments data acquisition system, run with LabView. A 5.08 cm hole was located directly below the microfiber intersection, allowing a resistance-heating element to rise up and ignite the fuel droplet. For all test cases except pure soybean oil the igniter remained near the droplet for 0.06 s, as determined by the high-speed video. For further details and pictures of the experimental setup, see Hoxie et al. [14].

2.2. Blend preparation

Blends of three component fuels were tested. In each blend RBD soybean oil, butanol and pentanol were present. The blends were produced on a volume basis at room temperature using 25, 50, and 33% of each component fuel. Blend composition is denoted by a, p, for pentanol, bu, for butanol and, sb, for soybean oil, followed by the percent volume in the blend. CHS in Mankato Minnesota processed the food grade RBD soybean oil. Chemical composition for the RBD soybean oil used in this research can be found in Schoo and Hoxie [15]. The butanol isomer was purchased from Cole–Parmer. The butanol isomer chemical composition used in this research can also be found in Schoo and Hoxie [15]. The pentanol isomer was purchased from Acros Organics and has a molecular weight of 88.15 g/mol with a chemical formula of $CH3(CH2)3CH2OH$ resulting in an elemental composition by weight of 68.13% carbon, 18.15% oxygen, and 13.72% hydrogen.

2.3. Experimental procedure

Prior to each trial, the Eurotherm controller brought the temperature in the furnace to 100 °C, however, for pure RBD soybean oil the furnace temperature had to be elevated to 200 °C in order for the fuel to ignite. The experiment was conducted under atmospheric pressure and normal gravity. A small droplet of fuel, approximately 1 mm in diameter, was then placed at the intersection of the microfibers using a pipette. The furnace was lowered manually. To begin the trial, the igniter was raised to just below the droplet using an air pressure system, and the heating element began the droplet combustion. The Lab View software tracked the temperature reading of both the side and upper thermocouples 10 times per second. The Motion Studio software was set to motion trigger, and thus the camera began recording once the igniter entered the frame. The camera operated at 300–400 frames per second for the duration of the droplet burn. Once the droplet had ceased to burn, the Lab View program continued to record temperature data until manually stopped.

An iPython-coded program was used to analyze the cross-sectional area of the droplet for each recorded frame of the trial. The program uses several different manually adjustable criteria to identify the edge of the droplet, and thus calculates an area quantity in units of square pixels. For more details on the edge finding program, see Greminger and Hoxie [16]. This data was used to create droplet area vs. time plots for the combustion process of each fuel blend.

Table 1 provides property data relevant to this study for each of the fuels tested in the experiments. Most notable are the disparate properties between the alcohols and the soybean oil. Also, the boiling point of pentanol is slightly above that of butanol, which is part of the reason it was chosen for this study. However, it is interesting to note that pentanol has a much lower vapor pressure and lower flash point temperature as compared to butanol.

3. Results and discussion

3.1. Pure fuels

A baseline reaction was recorded for each fuel type alone within the furnace. The pentanol and butanol droplets were ignited at a furnace temperature of 100 °C. The igniter was positioned slightly below the droplet for 0.06 s to initiate combustion. RBD soybean oil required a higher furnace temperature of 200 °C as well as a slightly longer time with the resistance heater near the droplet to ignite, due to its high flash point temperature of 321 °C. The additional heat required to ignite the pure soybean oil droplet is not anticipated to affect the characteristics of the combustion however, it may have had a slight impact on the reaction rate. The results are shown in Fig. 1. As can be seen, puffing and microexplosions are not present for the butanol and pentanol reactions. As single component fuels they burn smoothly without any secondary atomization events. RBD soybean oil is a multicomponent fuel and therefore exhibits some minor puffing, however it follows a similar trend to that of butanol and pentanol. Fig. 2 provides still shots from the high-speed video during combustion for each of the pure fuels. There are differences in flame luminosity that can be clearly seen between the three. Soybean oil burns with a strong yellow flame indicating soot productions, pentanol has a faintly visible flame and butanol reacts with no visible flame.

3.2. Binary fuel blends

Single droplet combustion was examined for an equivolume mixture of soybean oil and pentanol. The binary blend was tested to determine the effect pentanol has on the combustion of soybean oil as well as to provide a baseline for comparison. By comparing the binary combustion characteristics to the ternary combustion characteristics an observation could be made as to what synergistic effects result from burning a tertiary blend of soybean oil and alcohol. In addition, the binary blend of pentanol and soybean oil allows for comparison with previous studies conducted with