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Microexplosive combustion behavior of blended soybean oil and butanol droplets

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HIGHLIGHTS

- We analyze single droplet combustion behavior of RBD soybean oil-butanol blends.
- Ignition temperatures correspond to pure butanol for mixtures of 25% butanol and greater.
- Microexplosions occur for all mixtures tested.
- Microexplosions occur most frequently and with the highest intensity for mixture near equi-volume.
- Butanol level at microexplosion is higher for near equal volume concentrations.

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ABSTRACT

Experiments were conducted to examine the combustion characteristics of refined, bleached and deodorized soybean oil and butanol blends. Single droplets were suspended on microfibers in a combustion chamber at atmospheric pressure and ignited with a hot wire. Ignition characteristics and burning behaviors including burning to completion, burning with microexplosion and incomplete combustion were analyzed for initial concentrations ranging from 25–75% butanol. Droplet size and temperature measurements were analyzed throughout the droplet lifetimes. Relative concentrations prior and during combustion were estimated. Temperature measurements at ignition and during combustion were analyzed. The addition of butanol significantly lowered the ignition temperature. All mixtures studied ignited similarly to pure butanol droplets. The results were consistent with closed-cup flashpoint temperatures of butanol-soybean oil blends. A three-staged burn including a microexplosion was observed for all mixed droplets. Burning characteristics suggest a diffusion limited gasification mechanism, which has been previously linked to bi-component droplets with high volatility differentials. Microexplosions occur as a result of the more volatile component trapped within the droplet superheating at flame shrinkage. As butanol decreased to near equi-volume concentrations the microexplosions occurred earlier in the combustion process leading to higher concentrations of butanol trapped within the droplet at flame shrinkage. Therefore, equi-volume mixtures exhibited microexplosions with the greatest intensity. Blends of near equal concentrations by volume proved to exhibit the most favorable combustion characteristics. Bu40 exhibited the most violent microexplosions of all mixtures studied.

1. Introduction

Carbon dioxide produced from fossil fuel combustion is a major contributor of anthropogenic climate change. Volatility in petroleum prices and dwindling resource supply necessitate study of efficient methods of alternative fuel utilization. Biomass derived oils (BDOs) are an attractive alternative fuel option. They are domestically grown thus benefiting local economies, have comparatively short carbon life cycles and the infrastructure is in place for mass production. Two prominent biofuels are currently used for combustion applications, corn-based ethanol and soybean-based biodiesel. Biodiesel is produced through transesterification of soybean oil. Transesterification improves combustion characteristics by lowering viscosity and flashpoint through conversion of triglycerides to methyl esters. Production and utilization of ethanol and biodiesel has been largely dependent on tax incentives and government mandates. Currently many states have biodiesel and ethanol mandates for required blending with diesel and gasoline, respectively. However, several disadvantages exist with these fuel options. Ethanol, primarily produced from corn has had deleterious impacts on food prices, while the transesterification process

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comprises 60% of the total energy required to bring biodiesel to market. A recent study of the energy life cycle of soybean-based biodiesel performed by Pradhan et al. for the United States Department of Agriculture found that the fossil energy ratio of biodiesel is 4.56 [1]. Every portion of the biodiesel production process requires an energy input, from the presses required to extract oil from the soybeans to transporting the finished biodiesel to market. Energy required for these processes typically comes from a petroleum-based source. Therefore 4.56 represent the units of biodiesel that are delivered to market for every 1 unit of petroleum-based fuel input. The biodiesel energy life cycle study clarifies the need to develop methods for utilizing energy dense and highly viscous neat oils that biomass feedstocks produce. The energy required for conversion to biodiesel represents a significant reduction in energy efficiency; there is also a 10% conversion loss by mass associated with the production of glycerin during the conversion process. The influx of glycerin on the market due to biodiesel production has sent its price per pound down from twenty to five cents, effectively reducing it to a waste product. One method to improve utilization of biomass-based oils while maintaining low energy production methods is simple mixing with alcohols. A recent article by Law identified butanol as the most attractive alcohol for use as an alternative fuel source. As compared to ethanol, butanol has a higher energy content and volatility. Butanol exhibits characteristics, such as octane number similar to that of gasoline and is more energy dense than ethanol and methanol [1,2]. Also, a lower vapor pressure and higher miscibility than ethanol and methanol make butanol a more desirable fuel to pair with soybean oil (SBO). Blending butanol with SBO reduces the viscosity thus enhancing atomization. The lower flash point of butanol should also improve the ignitability of SBO eliminating the need for preheating and duel tank fuel systems. Soybean oil is produced in abundance in the United States with vast amounts in storage. It is the most economical BDO for producing BDO/alcohol blends. The investigation of both butanol and soybean oil in BDO/alcohol blends is therefore warranted.

Single droplet burning is an attractive analysis method for fuel characterization. Droplet testing is a low utilization, cost effective method for determining favorable combustion characteristics, based on fuel properties, for use in spray applications. Some multicomponent fuel droplets have been reported to experience "disruptive burning", or a staged burning behavior, while others exhibit a steady burn similar to a pure fuel. Microexplosion phenomenon is well documented for single droplet combustion of fuel blends with high volatility differentials [3–7]. Recently, Botero et al. documented the same phenomenon for blends of ethanol, biodiesel and diesel [3]. The disruptive burning process is characterized by three stages. The first stage is a steady reaction of the more volatile component. A short transient period follows where the flame becomes feeble (flame shrinkage) and the dominant surface concentration transitions from the more volatile to the less volatile component. As the droplet temperature increases towards the boiling point of the less volatile component a third stage of combustion is observed which often includes a microexplosion followed by the co-burning of the remaining fuels [3–7]. Microexplosions are the boiling and exploding of the more volatile component trapped in the droplet. Botero et al. suggests that the occurrence of microexplosions increases atomization and increases burning rate. Increased burn rates are attributed to increased mixing of fuel and oxidizer. This in turn reduces sooting propensity and NOx formation [3].

To understand what governs the combustion behavior of multicomponent fuel droplets experts have investigated mixtures of a variety of different fuel types and chemical properties. Water, alcohols, n-alkanes, n-alkenes and their mixtures are the most widely studied. Volatility differentials, initial droplet size and initial concentrations determine if disruptive burning and microexplosions will occur. Avedisian studied the mechanisms of microexplosions found to occur when water was present in fuel mixtures. They determined bubble nucleation occurred in the hydrocarbon phase and boiling temperatures were insensitive to high pressure. For binary mixtures the predicted and measured limits of superheat were also found to agree over the pertinent range of pressures [8–10]. Lasheras et al. determined that a volatility difference was required to produce microexplosions in a multicomponent fuel droplet [5]. Wang and Law determined that microexplosion intensity and frequency depend on mixture composition [4]. Wang et al. also found that microexplosions are dependent on droplet generation suggesting that they can be produced by entraining air upon droplet formation [6]. Zhang and Law studied the gasification mechanism; coming to the conclusion that it is intermediate between diffusion and distillation limited. And at high pressures the gasification mechanism further tends towards distillation controlled [7]. Ikegami et al. and Xu studied droplets of heavy oil under microgravity finding four stages of burning following a distillation-like vaporization mechanism. They also investigated light cycle oil and diesel in a furnace under atmospheric pressure. They determined that the rate constant was dependent on initial droplet size [11,12]. Droplet combustion studies of biodiesel have shown typical burning behaviors of multicomponent fuels; mixtures with ethanol have documented reduction in soot production and increased burning rates [3]. Research methods of droplet combustion have included experiments conducted under reduced gravity or "microgravity" conditions to keep droplets and flames spherical and reduce the effect of convection [11,13]. Researchers have used the method of free falling droplets or suspension from fibers of small diameter (7–110 μm) [3–6,8–10]. Ikegami et al. preferred the method of suspending droplets off of a thermocouple bead [11]. However, placing droplets on the cross section of two intersecting microfibers is the proven method for producing geometrically spherical droplets [9,14]. Microfibers exhibit a low thermal conductivity reducing increased evaporation rates due to internal droplet heating [9]. The majority of research groups set combustion chamber temperatures high enough for auto-ignition [3–6]. However, hot wire [12,14] and spark ignition [9] is used in some single droplet studies for ignition. It is expected that burning to completion would always occur using the auto-ignition technique because there is energy added in the form of heat to the burning droplet throughout its lifetime even after ignition. A spark or hot wire ignition technique allows the droplet temperature at ignition to be estimated and for the post ignition combustion process to be less dependent on external surroundings. The primary interests of experts performing tests on single droplets were ignition delay time [10], burning characteristics such as soot formation [6], burning rates [13], microexplosions and disruptive burning [3–5,11,14].

This paper presents combustion results obtained by igniting blends of pure refined, bleached and deodorized (RBD) soybean oil and 99% 1-butanol. The pure components were tested as well as blends of 25%, 40%, 50%, and 75% composition by volume of butanol. The mixtures are referred to as Bu100, Bu75, Bu50, Bu40, Bu25, and Bu0 where the number represents the percent concentration by volume of butanol in the mixture. The purpose of this work is to provide qualitative and quantitative information on ignition characteristics and burning behaviors of SBO/butanol blends. The experimental results were obtained using a combustion facility developed particularly for fuels of such nature as BDO/alcohol mixtures. The results are useful in predicting combustion behavior as a function of initial blend composition and droplet size. The gasification mechanism of single mixed fuel droplets during combustion is analyzed from experimental data and compared with previous research group's findings. Resultant phenomena