Fuel 167 (2016) 295–305

Contents lists available at ScienceDirect

Fuel

journal homepage: www.elsevier.com/locate/fuel

Droplet combustion characteristics of algae-derived renewable diesel, conventional #2 diesel, and their mixtures

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HIGHLIGHTS

- Droplet combustion characteristics of algal HRD are compared with DF2.
- Burning rates of algal HRD and R50 droplets are very close to those of DF2 in spite of chemical and sooting differences.
- HRD flames are less bright, suggesting less soot produced, than those of DF2.
- HRD may be an attractive additive and potential drop-in replacement for DF2 alone, or when blended.

ARTICLE INFO

Article history:
Received 28 August 2015
Received in revised form 8 November 2015
Accepted 11 November 2015
Available online 17 November 2015

Keywords:
Algae
Droplet combustion
Spherical symmetry
Algae-derived fuel
Diesel
Blending

ABSTRACT

Fuels derived from bio-feedstocks have received significant attention for their potential to reduce the consumption of petroleum-based liquid fuels, either through blending or direct use. Biofuels produced from heterotrophic microalgae are particularly attractive because of fast conversion of sustainable plant sugars into renewable oils of controllable quality and composition, but without the need for sunlight or carbon from the atmosphere for growth.

This paper describes the results of a fundamental study of the combustion characteristics of hydroprocessed renewable diesel fuel (HRD) produced from this strain of algae, and the results are compared to #2 diesel fuel (DF2) and an equi-volume mixture of HRD and #2 diesel (R50) as representative of blending. A canonical combustion configuration is used for a liquid fuel consisting of an isolated droplet burning with spherical symmetry and with fuel transport being entirely the result of evaporation at the droplet surface. This fundamental liquid fuel burning configuration is conducive to articulating the evaporation and sooting dynamics involved.

The results show that combustion rates and relative positions of the flame and soot aggregates to the droplet surface of HRD droplets are quite close to R50 and DF2 in spite of their significant chemical and sooting differences. These trends are explained based on similarities in the thermal properties of the fuels. Sooting propensity of #2 diesel is greater than that of HRD, with the mixture falling qualitatively in-between. The results suggest that HRD derived from heterotrophic microalgae can potentially be considered a drop-in replacement for DF2 or serve as an additive to DF2.

1. Introduction

Liquid fuels derived from bio-feedstocks are advantageous because they are renewable and may be compatible with the existing fuel infrastructure for transportation engines [1]. Such fuels have been produced from various oilseed crops such as sunflower [2], cottonseed [2], corn [3], and soybean [4]. Concerns over land use for feedstock growth have motivated the development of alternative approaches that use marginal land, require less consumable water, and can mitigate emissions of greenhouse gases. In this context, algae is receiving attention as a promising feedstock due to its potential for high production rates, rapid growth cycles, and high lipid content [5].

An attractive strain of algae is heterotrophic algae. This form of algae can be produced in both the presence and absence of light. In dark conditions, the energy for growth comes from organic carbon dissolved in the culture medium, and a supply of CO_2 is not needed.

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http://dx.doi.org/10.1016/j.fuel.2015.11.036

Nomenclature

C_p	specific heat
D	droplet diameter
D_o	initial droplet diameter
D_s	soot shell diameter
D_f	flame diameter
D_{fiber}	fiber diameter
H	major axis of an AOI ellipse
K	burning rate
k	thermal conductivity
MW	molecular weight
W	minor axis of an AOI ellipse
t	time

Greek letters

ν	stoichiometric coefficient
ρ_L	liquid density
Φ_K	defined parameter in Eq. (2)
Φ_F	defined parameter in Eq. (3)

Subscripts

s	soot shell
f	flame
g	gas or vapor state

These advantages alleviate constraints on growing algae that favor geographical regions which receive significant daily light while requiring CO_2. Heterotrophic algae is, therefore, promising as a biofuel feedstock which could meet the fuel needs of the transportation sector since it de-couples oil production from both geography and seasonality.

There are two broad pathways to produce biofuels from algal lipids: trans-esterification and hydrogenation [6]. Trans-esterification of algal oils produces algal "biodiesel" (BD), consisting of long chain fatty acid methyl esters (FAME) [1], and glycerin as a co-product. Hydrotreated renewable diesel (HRD, "green" diesel) is produced by removing oxygen molecules to saturate double bonds [7,8]. While a significant amount of work has been reported on the production and life cycle evaluation of algal BD [6,8–17] and algae-derived HRD [6,8,18,19], little research has been reported on fundamental combustion properties of these fuels. Most desirable outcome for an algae-derived fuel is to be a 'drop-in' replacement [20] for a petroleum fuel. However, information does not currently exist to assess this potentiality.

Most of the reported research on algal biofuels focused on system-level evaluation of HRD and BD. For example, the in-cylinder performance of diesel engines fueled by algae BD [21–23], mixtures with diesel fuel [22–27], and HRD [28,29] was studied. A 50/50 blend of algal HRD with NATO F-76 (similar to #2 Diesel fuel) was also examined in a gas turbine engine [30,31]. Furthermore, a study of marine gas turbines to certify algal biofuels for Navy marine systems [30] showed a connection between engine starts (ignition) and fuel properties, but little else could be extracted from the results that extends beyond the engine used to obtain the information.

Engine tests yield useful information about combustion performance under realistic conditions. However, the environment of an engine is overly complex for extracting fundamental information about mechanisms that control combustion because of the complex turbulent transport present and the time-dependent volume of the combustion zone. The information is often unique to the specific engine design employed in the experiments. A low-dimensional transport configuration for combustion can facilitate the development and interpretation of experimental observations. For a liquid fuel the simplest configuration that still has a connection to liquid spray injection is that of an isolated droplet burning in an environment that promotes spherical symmetry in the gas, with transport processes that arise only as a result of the evaporation of the fuel at the droplet surface [32,33]. Fig. 1 illustrates such a canonical configuration of liquid fuel combustion.

A single stationary isolated droplet is ignited and burns in a quiescent environment without the influence of forced or buoyancy-induced convection. The gas flow is created entirely by the evaporation process. Under these conditions, the streamlines of the flow are radial, resulting in spherical symmetry in the gas phase: the flame is then spherical and concentric with the fuel droplet, and if soot forms, the soot aggregates are trapped between the droplet and the flame where the forces (i.e., due to evaporation-induced velocity and thermophoresis) acting on the soot particles balance [34]. Despite its simplicity, the spherically symmetric droplet burning configuration involves a large number of the physical and chemical processes relevant for the much more complex flows encountered in sprays and engines [35], including unsteady gas and liquid transport, preferential vaporization, moving boundary effects, variable fuel properties, detailed combustion kinetics, soot formation, and radiation effects, making it ideally suitable for model development and validation.

To the authors' knowledge, no experiments have been conducted for algae-based liquid fuels in environments that promote the combustion symmetry depicted in Fig. 1. The present study does so specifically for algae HRD. HRD was selected because it is more widely available than algal biodiesel from trans-esterification, and may have a greater potential for adoption as a transportation fuel due to its chemical characteristics (e.g., energy density, cetane number, storage stability) [36]. In addition, HRD meets the ANSI D975 diesel standard [6,8].

In this paper, the combustion performance of HRD, as measured by the evolution of droplet, soot shell, and flame diameters, is compared with conventional #2 diesel (DF2), and a 50% DF2 and 50% HRD mixture on a volume basis (denoted "R50", to follow prior engine studies [30,31] that evaluated performance of equi-volume mixtures). The experimental methods and chemical analysis are described in Section 2, while the results and subsequent analyses and discussions can be found in Section 3. A summary is provided in Section 4.

2. Experimental methods

2.1. Design

Spherical symmetry is promoted by using "small" droplets with initial diameter D_o between 0.52 and 0.55 mm, restricting their motion by anchoring them to very small support structures (or fibers), employing a stagnant ambient in the experiments, and minimizing the effects of buoyancy by carrying out the experiments at low gravity (on the order of 10^{-4} of normal gravity on Earth). The ambient for the data reported here is air at room temperature and atmospheric pressure. A brief outline of experimental design and procedures is given below. More details are provided in [37–39].

Droplets with the desired size are deployed at the intersection of two SiC fibers (~14 μm diameter) so that the droplet will not move throughout its burning history. Fig. 2a shows a planar view