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Characterization of the surface tension of vegetable oils to be used as fuel in diesel engines

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HIGHLIGHTS

- ▶ Existing diesel engines can be fueled with straight vegetable oils.
- ▶ Vegetable oils surface tension is higher than the one of diesel fuel.
- ▶ Surface tension has a deep impact on the combustion of existing diesel engines.
- ▶ Vegetable oils surface tension is reduced to match diesel fuel values by heating.
- ▶ Straight vegetable oils heating temperature should be about 120 °C.

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ABSTRACT

Straight vegetable oils may be used as fuel in existing diesel engines. However, some precautions should be taken into account because some of their physicochemical properties must be adjusted through temperature control to ensure enhanced combustion, thus avoiding premature aging of the engine. Although it is well known that surface tension plays a prevalent role in the fuel atomization process which affects the combustion quality, there is lack of published information about its variation with temperature when dealing with straight vegetable oils to be used as fuel in unmodified diesel engines. In this work, the surface tension of several vegetable oils is studied in a wide temperature interval. The optimal range of temperatures at which each vegetable oil should operate to adjust its properties to those of automotive diesel and biodiesel is found. Moreover, an empirical relationship between the dependence between surface tension and density is presented. Therefore, by means of this relationship, just measuring the density of a given oil, its surface tension can be directly deduced.

1. Introduction

Due to the diminishing reserves and world price instability in petroleum fuel, the rising demand for energy and concerns about global warming, at the present time there is a growing interest in renewable energy sources and in biofuels in particular [1]. Nowadays diesel engines are being widely applied in sectors including road and train transport, maritime propulsion, or agricultural among others [2]. This is due to their appealing features such as high economic feasibility [3] and high torque and durability, as well as the possibility of running with several types of fuels, including diesel fuel, straight or transesterified vegetable oils or short chain alcohols, and mixtures such as diesel/vegetable oil or diesel/ethanol/vegetable oil in different proportions [2].

Small-scale produced straight vegetable oils (SVOs) are considered as renewable fuel being attractive because of its environmental benefits [4,5]. SVO is a biofuel obtained from plant seed oil pressing. It can be used in non-modified diesel engines just by adding a small heat exchanger in conjunction with other minor modifications in the fuel intake system [6].

SVO can be small-scale produced in local cooperatives [7,8] through pressing, filtering and conditioning processes which are much simpler than the ones required for biodiesel (BD) production. Thus, the straight use of vegetable oils in existing diesel engines avoids the transesterification stage required to obtain BD, lowering the energy consumption and reducing considerably the environmental impacts due to less harmful emissions and fewer chemicals consumption [4]. The most widely used SVOs for biofuels purposes – currently mostly for biodiesel production – are in decreasing order palm oil, soybean oil, rapeseed oil and sunflower oil among others [9].

Although there are some similarities between most of the available vegetable oils and automotive diesel fuel, they present some physicochemical differences. Hence, some precautions must be adopted when using SVOs as fuel in existing diesel engines [6].

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The disadvantages of SVOs are higher kinematic viscosity and surface tension, thereby making the SVOs atomization difficult. The main injection and atomization properties related to the quality of fuel ignition are density, viscosity and surface tension [2,10]. Higher surface tension and viscosity of SVOs compared to automotive diesel fuel produce worse fuel atomization, which in turn leads to higher spray tip penetration and higher Sauter mean diameter (SMD) of the spray droplets [11–13]. As the spay features have an important role on the quality of combustion, a method for improving the spray characteristics is needed [14].

It is well-known that fuels with lower density, viscosity and surface tension compared to diesel present lower average droplet size, which may promote earlier fuel injection and better atomization in diesel engines. It has been reported that engine combustion, emissions and performance are directly related to spray atomization and fuel–air mixing [15]. Therefore, the spray characteristics are improved due to the fineness of atomization which reduces the fuel ignition delay [16]. Ignition delay is greatly affected by the initially vaporized fuel fraction. Consequently, the ignition delay rises with an increasing boiling point, because to vaporize the initial fuel fraction, more time is required. However, the ignition delay may be controlled by other variables such as the cetane number [17], mixture temperature, vapor, and oxygen concentration [18]. Extended ignition delays allow reducing the particulate matter (PM) formation since more time is available for premixing [19]. Reductions in PM emissions may be attributed to more complete fuel combustion [20]. In addition, when dealing with diesel fuel it has been reported that NOx emissions can be significantly reduced by applying early injection timing [19]. Poorly atomized fuels cause the jet to become a solid steam instead of a spray composed of small droplets [21] resulting in poor combustion that produces black smoke and emissions of pollutants [22] and PM [19]. Poorly atomized fuels also promote the development of carbon buildup in the combustion chamber, which may have harmful effects in the engine [3]. Additionally, adequate atomization enhances engine efficiency [23].

When dealing with biodiesel-blended fuels it has been reported that atomization worsens with the biodiesel mixing ratio due to the increase of viscosity and surface tension in the mixture [22]. However, according to Di et al. [24], biodiesel has a higher oxygen content than diesel fuel which contributes to more complete combustion, especially in reducing HC, CO, toluene and xylene emissions while inhibiting soot formation and PM emissions in diesel engines [17]. Similarly, different oxygenic additives allow reducing engine emissions [25]. Additionally, in [15] it is stated that both a higher oxygen content and adequate spray atomization may reduce soot formation. Nevertheless, biodiesel presents higher NOx emissions than diesel fuel, which are attributed to the increased oxygen level in the combustible mixtures and the higher combustion temperature [24].

The effects of using vegetable oils in unmodified diesel engines will greatly depend on the engine sensitivity to fuel injection and on the combustion characteristics of the vegetable oil [26,27]. Existing diesel engines have fuel-injection systems that are susceptible to physicochemical changes [28]. According to Agarwal et al. [29] when using SVOs as fuel in unmodified diesel engines, short-term tests show good performance; however, long-term tests indicate higher particulate emissions as well as problems related to injection coking, increase in cylinder deposits, ring sticking and unburned fuel in the lubricating oil. It is well accepted that fuel physicochemical properties such as density, viscosity and surface tension are the most influencing injection and atomization properties related to the quality of ignition in compression engines [2,30] besides the geometry of the injection system [31]. Consequently, a deep knowledge of their values in a broad range of temperatures is fundamental to characterize the performance of SVOs as fuel.

The method suggested in this paper is to reach appropriate physicochemical properties values and to obtain improved jet injection by applying a suitable heating of the SVO before the injectors by means of an electrical heater. Once properly heated, SVOs become very similar to automotive diesel fuel in terms of physicochemical properties. Thus, it is not necessary to make further changes in the diesel engine, being the modifications needed to use SVO as fuel in existing diesel engines very simple.

Several works have been done to test several physicochemical properties and performance parameters of different fuels, but surface tension has received very little attention [32]. Moreover, although surface tension plays an important role in the evaluation of fuel performance, the authors of this work have not found published studies devoted to study the SVOs surface tension and its dependence with temperature with the purpose to be used as fuel in existing diesel engines.

The aim of this work is to obtain a deep knowledge about the temperature dependence of surface tension of commonly used vegetables oils. Mathematical expressions of its temperature dependence are derived to characterize the analyzed SVOs. Additionally, the surface tension of the vegetables oils analyzed is compared with the ones of commercial pure biodiesel and automotive diesel fuel. From this comparison the heating temperature range to match the surface tension of pure biodiesel and automotive diesel fuel is obtained. Moreover, a method to calculate the surface tension from the density measure is proposed. This method is highly attractive since the density measurement is much simpler, economical and less time consuming than the surface tension measurement.

The fuel molecular structure greatly influences its surface tension. The surface tension is affected by the fatty acid hydrocarbon chain length and the number of unsaturated bands. Long fatty acid hydrocarbon chain tends to increase the surface tension [33]. Table 1 gives a listing of the vegetable oils analyzed in this work and their fatty acid composition given in mass percent.

2. Methodology

2.1. Surface tension

Surface tension is a physical property of a liquid caused by the cohesive forces between liquid molecules [34,35]. Liquid molecules placed within the bulk of a liquid are completely surrounded by like molecules so that the forces of attraction between adjacent molecules are equal in all directions. Conversely, the molecules on the surface of the liquid at the liquid/gas interface present unbalanced forces, resulting in an inward attraction. The surface tension is the force per unit length along the surface film of a liquid in the liquid/gas boundary which causes the film to behave like an elastic sheet [34]. Due to surface tension, the molecules in a liquid/gas interface are in tension and tend to contract in a minimum surface area [36].

Surface tension has a deep influence on the final quality in many products such as fuels, detergents, ink jet products, pharmaceuticals and lubricants among others. Additionally, surface tension plays an important role in processes as wetting, penetrating, foaming or droplet formation of a liquid [35], thus governing the chemical and physical behavior of liquids. Surface tension depends on variables such as temperature, pressure and, in case of mixtures, composition.

In case of fuels destined to internal combustion engines, surface tension greatly influences the droplet formation in the injection system as well as the atomization properties related to the quality of ignition [2].