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Optical fiber sensor temperature coded for concentration measurement of oil–biodiesel blends

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ABSTRACT

This work describes the operation of an optical fiber sensor employed in the determination of remaining oil concentration in oil–biodiesel blends. The sensor is based both on the sensitivity of a long period grating to changes in the surroundings refractive index and on the thermo-optical properties of oil–biodiesel blends. The sensor response is provided by a temperature coded interrogation unit that employs an auxiliary fiber Bragg grating. The standard metrological analysis of an optimized sensor showed that is possible to detect until 0.10% v/v of oil in oil–biodiesel blends.

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1. Introduction

Nowadays, the environmental problems caused by the indiscriminate use of petroleum, the increasing pressure to reduce global emissions of greenhouse gases, the finite nature of fossil fuels and the growing of the eco-friendly market are leading researchers and industries to explore fuels derived from biomass conversion: the biofuels. In this scenario, biodiesel has been employed as a diesel additive to reduce levels of particulates, carbon monoxide and hydrocarbons from diesel-powered engines [1,2]. However, in order to achieve the biodiesel benefits, it is necessary to assure its quality in both manufacture and distribution networks. In general, the biodiesel is produced through a chemical process, the transesterefication, which converts triglycerides to alkyl esters [3–5]. This process results in methyl or ethyl esters (biodiesel) and glycerin as well as an incomplete reaction results in partial conversion of the triglycerides. In addition, oil can also be illegally added to biodiesel compromising the product quality [6,7].

The development of techniques to assess the quality of biodiesel has been a subject of some works in the last years [8,9]. Methods based on proton nuclear magnetic resonance [10,11], capillary gas chromatography [12,13], high-performance liquid chromatography [14] and direct infusion electro spray ionization mass spectrometry fingerprinting [15] have been reported in the literature. These techniques frequently require sample preparation, previous calibrations for analysis, long-time for analysis and high-cost equipments. Alternative and practical analytical methods have been proposed in order to allow field analysis along the biodiesel production, handling and storage processes. In a sense, near infrared spectroscopy [16], Fourier transform infrared [6,7] and Raman spectroscopy [6] present as possibilities for rapid, easy-to-handle, and cost effective monitoring of both transesterification reaction and biodiesel quality. However, accuracy and precision of these spectroscopy techniques typically depend on calibration models based on multivariate analysis such as principal component regression, partial least square regression or artificial neural network [6]. Refractive index measurements [17] and photothermal methods based on thermal lens spectrometry and open cell photoacoustic [18] have also been cited as alternative techniques for evaluating the biodiesel. Within this context, optical fiber grating sensors based on long period gratings (LPG) are useful and attractive tools for such purposes [19,20]. The main features of these devices are the small physical size, the immunity to electromagnetic interference, the electrical and chemical passivity, the low response time, the capability of integration with portable and automatic systems, and the high sensitivity to refractive index. Approaches proposed to interrogate LPG sensors can be classified into interferometric techniques and techniques based on intensity. Techniques based on intensity have a lower cost, which is an important factor for its field implementation.

In this work thermo-optical properties of oil–biodiesel blends and a sensor based on the refractometric properties of an LPG were used to identify the oil concentration in different oil–biodiesel blends. In the sensor set-up, interrogation is performed by an FBG connected in-series with the LPG. Despite the well known use of these devices for sensing, the new configuration presented in this work provides a sensor coded in temperature. The key for

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the sensor operation is the measurement of the sample temperature that provides a minimum value for the signal intensity transmitted through the device. Performance of the technique for determining the remaining oil concentration in oil–biodiesel blends was evaluated according to standard metrological analysis.

2. Methodology

Oil–biodiesel blends were prepared by adding sunflower oil and biodiesel in different proportions, resulting in samples with oil concentrations of: 0, 20.0, 40.0, 60.0, 80.0 and 100.0% v/v (error limit of 0.1% v/v). The refractive indexes of samples were measured at 26.0 °C with an Abbe refractometer (Atago, DR-A1) with resolution of 0.5×10^{-4} refractive index units (RIU), operating in sodium D-line at 543.5 nm. The thermo-optic coefficients (dn/dT) of oil and biodiesel were determined for a temperature range between 14.0 and 35.0 °C with the help of a calibration thermostatic bath (Lauda – Ecoline Staredition E200). LPG was engraved in a standard telecommunication (SMF) optical fiber by point-to-point technique using the electrical arc discharge from a fusion splicer, resulting in a device with period of 595 μm and length of 35.7 mm. After the LPG was inserted in a sample glass cell, one of the fiber tips was bond and a strain was applied to the fiber by means of a 10 g mass hung on the other fiber tip. LPG spectra when in contact with the oil–biodiesel samples were measured at temperatures from 20.0 to 120.0 °C, with incremental steps of 2.0 °C. The temperature was measured by a type-K thermocouple, with a resolution of 0.05 °C, inserted in the sample glass cell close to the LPG. A super-luminescent LED (MRV Communications, central wavelength at 1547.1 nm, half bandwidth of 54.8 nm) and an optical spectrum analyzer (OSA, Anritsu-MS9710B, minimum wavelength stability of 10 pm and level stability accuracy of 0.04 dB) were used to acquire the LPG transmission spectrum. An FBG was connected in-series with the LPG to provide the sensor output signal. FBG reflected spectrum was measured by using an optical circulator, the OSA and the LED, according to Fig. 1. FBG was photo-written in a hydrogenated SMF optical fiber by direct illumination of a phase-mask with a KrF excimer laser. In order to avoid cross-sensitivity effects, FBG was kept at (20.0 ± 0.5) °C and without mechanical deformations during the experiments. With this setup, light intensity reflected by the FBG depends only on the LPG response. Consequently, as the oil–biodiesel blends properties affect the LPG response, the detected FBG reflection spectrum carries information about the blend constitution. The main metrological characteristics of this thermally coded and optimized optical sensor were determined according to standard approach reported in [21]. FBG responses were measured 4 times under repeatability conditions (one cycle of oil–biodiesel blends heating) and 3 times under reproducibility conditions (the liquid sample was removed after each measurement and reinserted before the next measurement).

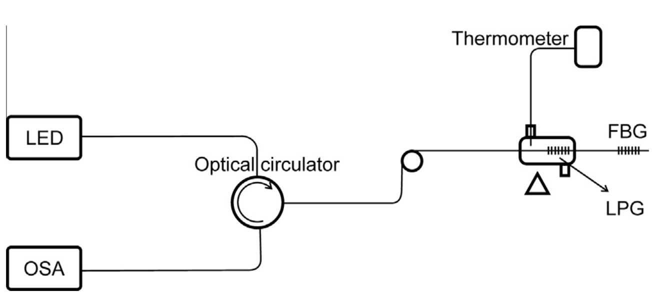

Fig. 1. Schematic of thermally assisted and optimized optical fiber sensor for evaluating oil–biodiesel blends based on FBG intensity response.

3. Results and discussions

3.1. Oil–biodiesel blends: temperature dependence of the refractive index

Refractive indexes of the oil–biodiesel blends at (26.0 ± 0.5) °C are shown in Fig. 2(a). The error bars are the combined standard uncertainties calculated according to standard uncertainties inherent to both the experimental standard deviation of the mean of refractive index, measured 4 times under repeatability and 3 times under reproducibility conditions (Type A uncertainties), and the refractometer resolution uncertainty (Type B uncertainty). Type B uncertainty was modeled as symmetric rectangular probability distribution. When oil is added to biodiesel, refractive index of the samples raises from 1.45440 ± 0.00013 (pure biodiesel) to 1.47190 ± 0.00013 (pure oil) with a rate of $(1.780 \pm 0.016) \times 10^{-4}$ RIU/% v/v of oil in the mixture. At typical environmental temperatures the refractive indexes of oil–biodiesel blends are close to or higher than the cladding refractive index of the silica (1.4575 ± 0.0004 at (20.0 ± 0.5) °C) [22]. However, the temperature can be used to change this condition once oil and biodiesel refractive indexes change with the temperature due to thermo-optic effect. Fig. 2(b) shows the results of the thermo-optical characterizations of oil and biodiesel samples. These liquids present negative thermo-optic coefficients; consequently, a temperature increase causes a decrease in the refractive index. Additionally, as

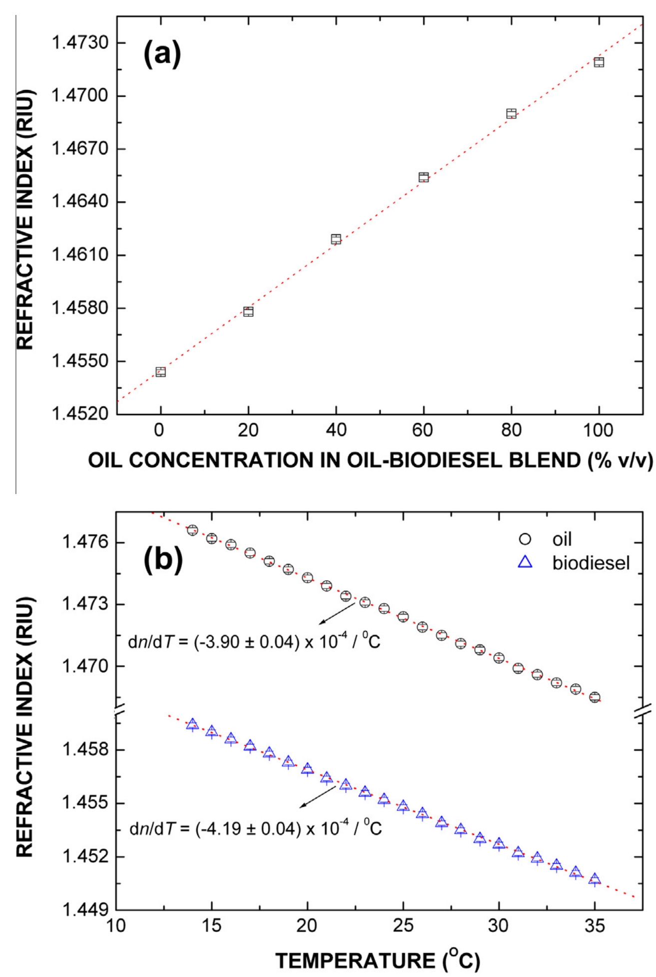

Fig. 2. Refractive index of the: (a) oil–biodiesel blends at 26.0 °C and (b) oil and biodiesel in the temperature range between 24.0 and 35.0 °C. Dotted lines are the best linear fit to the experimental data.

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