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## The use of thermal lens spectroscopy to assess oil–biodiesel blends

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### HIGHLIGHTS

- ▶ Thermal lens and mass diffusion effects to assess oil–biodiesel blends.
- ▶ Thermal and mass diffusivities give significant information on oil–biodiesel blends.
- ▶ Thermal lens spectroscopy can be used to certify the quality of biodiesel.

### ARTICLE INFO

#### Article history:

Received 26 March 2012

Received in revised form 15 August 2012

Accepted 16 August 2012

Available online 1 September 2012

#### Keywords:

Thermal lens spectroscopy

Thermal diffusivity

Mass diffusivity

Oil–biodiesel blends

### ABSTRACT

Thermal lens (TL) spectroscopy in a dual-beam configuration was applied in a study on biodiesel and oil–biodiesel blends. The goal of this work was to evaluate the behavior of the thermal and mass diffusivities that arose when oil was added to biodiesel and to verify the capability of the method to identify small concentrations of triacylglycerol in biofuel. When transitioning from pure biodiesel to a blend consisting of 98% biodiesel and 2% soybean oil, the thermal diffusivity decreased 15% and the mass diffusivity increased 59%, which indicated that both parameters can provide significant information about the presence of oil in biodiesel. Therefore, TL spectroscopy can be a useful method for certifying the quality of biodiesel and biodiesel blends.

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### 1. Introduction

It is well known that biodiesel is an alternative fuel that is economically competitive, environmentally healthy and easily available. As such, biodiesel constitutes a viable alternative to traditional fuel, particularly for compression-ignition engines, because, in addition to being a renewable energy source, it can be used directly in existing fuel engines [1]. Currently, the modern diesel engine can operate with 5–10% biodiesel having been added into the total volume of diesel without any efficiency loss [2].

Biodiesel can be produced from a variety of raw materials. Production generally occurs through a transesterification process in which a vegetable oil or animal fat reacts with methyl or ethyl alcohol. This reaction occurs in the presence of a catalyst, which is generally basic, and primarily forms biodiesel (ester) and glycerol [3,4]. Following the reaction, small amounts of triacylglycerol can remain in the final biodiesel product. In addition, traces of

glycerol, residual alcohol and the catalyst can remain, and these substances contaminate the final product; therefore, detecting these traces is critical in biodiesel quality control. Contaminants or impurities can cause serious operational problems when biodiesel is used because they may easily clog an engine's filter. Because of this problem, it is extremely important to monitor the steps involved in biodiesel production to recognize and fix any possible problems that may have been created during the transesterification procedure. To do so, a rigorous system of quality control is necessary to achieve commercial success in the production of biodiesel [5]. Thus, it is important to search for methods that are able either to standardize and certify biodiesel or to indicate the presence of impurities [6].

A methodology used to study biodiesel and its blends that has been explored only to a very limited extent is thermal lens (TL) spectroscopy, which can characterize the thermo-optical properties of different types of materials [7]. TL spectroscopy is a high-sensitivity optical technique that has been applied in the study of samples with a small optical absorption, and it is attractive because it is neither destructive nor invasive and could possibly be used at gas stations to directly analyze the quality of oils and biofuels. Castro et al. were the first to use the TL method for different biodiesel samples. They concluded that, because of the simplicity

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of the method, it can be applied both in the study of the physico-chemical properties of biodiesel and for certification purposes [8]. Subsequently, Lima et al. used a single-beam TL configuration to indicate the presence of impurities, such as antioxidants, residual catalysts and alcohol, in biodiesel [9]. More recently, the same TL experimental setup was used to characterize biodiesel and diesel and to distinguish biodiesel–diesel blends [10].

In the present work, a dual-beam TL experimental configuration was used to characterize soybean oil, biodiesel and soybean oil–biodiesel blends. To obtain the oil–biodiesel blends, soybean oil was added to biodiesel in a quantity no smaller than 1% and no larger than 5% of the total volume of the biodiesel, which would, therefore, be anywhere from 99% to 95% biodiesel. In the context of this work, soybean oil (triacylglycerol) was regarded as an impurity (i.e., a contaminant) in the biofuel (ester), and our aim was to verify the capability of the TL method to identify small concentrations of this type of impurity in biodiesel.

## 2. Materials and method

The samples of refined soybean oil (SO) and biodiesel (B) were acquired through local commerce in Brazil. The soybean oil–biodiesel (SOB) blends were prepared in the laboratory according to the concentrations indicated in Table 1.

The SO, B and SOB samples were analyzed using a time-resolved TL technique in a dual-beam mode-mismatched configuration. Fig. 1 shows a schematic diagram of the TL experimental setup that was used in the measurements. This method was based on the TL effect, which is created when laser radiation with a Gaussian intensity distribution profile (an excitation laser) focuses on a material and a fraction of absorbed energy produces a radial temperature change  $\Delta T(r)$  [11,12]. This variation in the temperature causes a change in the refractive index of the material in the heated region, and this change is proportional to  $\Delta T(r)$ . When a wave front from another laser (a probe laser) crosses the heated region, it under-

goes a phase variation, which results in either divergence or convergence of the beam, depending on the nature of the material. By controlling this beam profile in the far field (Ph<sub>2</sub> in Fig. 1), some thermal–optical properties of transparent materials, such as thermal diffusivity, can be studied.

In the configuration that was used, the sample was inserted in a quartz cuvette with a thickness of 1 mm, which was then placed in the minimum position of the beam waist of an Argon laser that was tuned at  $\lambda_{ex} = 514.5$  nm (the excitation laser), and the TL effect was probed by a HeNe laser at 632.8 nm (the probe laser). The intensity  $I(t)$  of the probe laser in the far field was monitored as a function of time. The theoretical model developed by Shen et al. [11] was used to fit the TL experimental data; this model is expressed by the following equation: which is expressed by:

$$I(t) = I(0) \left\{ 1 - \frac{\theta}{2} \arctan \left[ \frac{2mV}{\left[ (1+2m)^2 + V^2 \right] \left( \frac{t_c}{2t} + 1 + 2m + V^2 \right)} \right] \right\}^2 \quad (1)$$

In the above equation,  $I(0)$  is the signal intensity when either  $t$  or  $\theta$  is zero;  $t_c = w_{oe}^2/4D_{Th}$  is the characteristic time constant of the TL effect's formation;  $w_{oe}$  (m) is the beam's radius in the sample position;  $D_{Th}$  (m<sup>2</sup>/s) is the thermal diffusivity;  $V = Z_1/Z_c$ , with  $Z_1$  (m) being the distance between the minimum beam waist and the sample position;  $Z_c = \pi w_{op}^2/\lambda_p$ , with  $w_{op}$  (m) being the minimum beam radius and  $\lambda_p$  (nm) is the probe beam's wavelength; and  $m = (w_{1p}/w_{oe})^2$ , with  $w_{1p}$  (m) being the probe beam's radius in the sample position. To gain a better understanding of the geometric beam's position around the sample, please see Fig. 2, which shows an outline of the experimental setup and lists the default parameters: in our setup,  $w_{oe} = (45.9 \pm 0.9)$   $\mu\text{m}$ ,  $w_{op} = (151 \pm 3)$   $\mu\text{m}$ ,  $Z_1 = (0.205 \pm 0.005)$  m, and  $Z_c = (0.113 \pm 0.005)$  m. The distance between the sample and the detector ( $Z_2$ ) was approximately 4 m, which means that  $Z_2 \gg Z_c$  and this is the condition that implies  $V = Z_1/Z_c$ .

According to the TL theoretical model,  $\theta$  is proportional to the induced phase difference in the probe laser after it passes by the heated area of the sample, and the equation for  $\theta$  is as follows [11,12]:

$$\theta = - \frac{PAL}{K\lambda_p} \frac{dn}{dT} \quad (2)$$

in which  $P(W)$  is the incident power,  $A$  (m<sup>-1</sup>) is the absorption coefficient at the excitation wavelength  $\lambda_e$  (nm),  $L$  (m) is the cuvette thickness,  $K$  (W/Km) is the thermal conductivity,  $dn/dT$  (K<sup>-1</sup>) is the refractive index temperature coefficient and  $\phi$  is the fraction of the absorbed energy that is converted into heat.

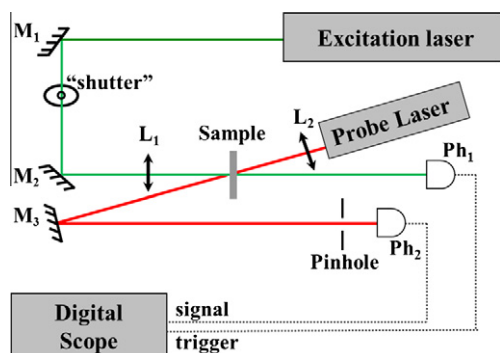
## 3. Results and discussion

### 3.1. Soybean oil and biodiesel

Fig. 3 shows the characteristic TL transients for both refined soybean oil (SO) and biodiesel (B) over a short time interval (a) and a long time interval (b). The SO and B samples were excited at 514.5 nm and had incident powers of 15 and 2 mW, respectively. Because B has a larger TL effect than SO in the excitation wavelength that was used, the measurements could not be developed using the same excitation power. Thus, the powers were chosen so that the amplitudes of the TL signals were approximately 10%, which is within the limit proposed by the theoretical model of the TL (i.e.,  $\theta < 20\%$ ), and so the visual comparison was easier. For a short time interval, the experimental data are in very good agreement with the theoretical model of the TL, which is described by Eq. (1). Based on the fit, both  $\theta$  and  $t_c$  could be determined. The values of  $t_c$  were  $(5.0 \pm 0.1)$  and  $(4.0 \pm 0.1)$  ms for the SO and B

**Table 1**  
The concentrations of biodiesel (B), soybean oil (SO) and soybean oil–biodiesel (SOB) blends that were studied in this work.

Biodiesel ml (%)	Soybean oil ml (%)	Definition
5 (100)	0 (0)	B
4.95 (99)	0.05 (1)	SOB <sub>1</sub>
4.90 (98)	0.10 (2)	SOB <sub>2</sub>
4.85 (97)	0.15 (3)	SOB <sub>3</sub>
4.80 (96)	0.20 (4)	SOB <sub>4</sub>
4.75 (95)	0.25 (5)	SOB <sub>5</sub>
0 (0)	5 (100)	SO



**Fig. 1.** The dual-beam TL experimental configuration: the items labeled L are lenses, the items labeled M are mirrors, and the items labeled Ph are the photodetectors.

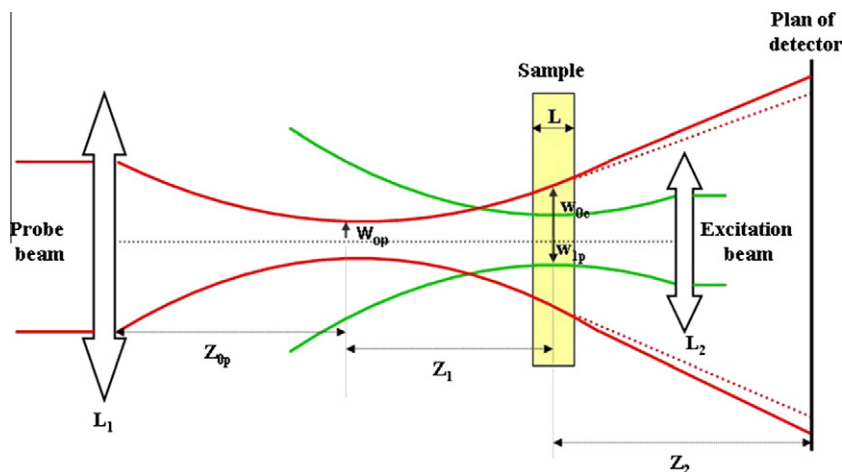


Fig. 2. An outline of the geometric beam position around the sample:  $w_{oe} = (45.9 \pm 0.9) \mu\text{m}$ ,  $w_{op} = (151 \pm 3) \mu\text{m}$ ,  $Z_1 = (0.205 \pm 0.005) \text{m}$ , and  $Z_c = (0.113 \pm 0.005) \text{m}$ .

samples, respectively. Because  $t_c = w_{oe}^2/4D_{Th}$  and  $w_{oe} = 45.9 \mu\text{m}$ , the quantities  $D_{Th} = (1.05 \pm 0.02) \times 10^{-7}$  and  $D_{Th} = (1.31 \pm 0.03) \times 10^{-7} \text{m}^2/\text{s}$  were obtained for the SO and B samples, respectively. The value of  $D_{Th}$  that was obtained for the SO sample is in agreement with the values found in the literature for soybean and sunflower oils [13]. The value of the thermal diffusivity for B is 10–16% higher than the value found in the literature for biodiesel produced in different ways and using different sources [8]. This disagreement can be attributed to both the varying concentrations of fatty acid esters and the purity level of the samples; because our sample was a commercial one, it was expected that the industrialization process was sufficiently rigorous to obtain a high degree of purity. In our recent work, we concluded that, when biodiesel is cleaned adequately, more impurities are eliminated from it and an increase in its thermal diffusivity can be observed, which indicates that the solution has a low viscosity [9]. Another assumption that needs to be considered is that a high value for  $D_{Th}$  for biodiesel is an indication of a low percentage of triacylglycerol that has not been transesterified but is present in the biodiesel nonetheless. This assumption was confirmed in our sample by means of chromatographic analyses, which indicated that 98.4% of our biodiesel sample consisted of ester. This percentage is in good agreement with Brazilian standards, which establish that biodiesel must be 96.5% ester to be commercialized [14].

Over short time intervals, the TL effect was predominant in both samples. The amplitude for the SO sample could be attributed to the contribution of different molecules, such as triacylglycerol (98.4%), that are constituted by diverse and numerous fatty acids or to natural antioxidants, such as  $\beta$ -carotene, chlorophyll a and b, and other, non-natural antioxidants. Although its concentration was highest in the SO sample, triacylglycerol was not primarily responsible for the TL signal because its absorption in the visible spectrum is very small when compared to the absorption of impurities, such as  $\beta$ -carotene.

Thus, because all molecules with a chemical composition that is different from the triacylglycerol in the SO sample were defined as impurities, we can assume that they were primarily responsible for the TL signal amplitude. In this context, in the case of the B sample, the TL signal amplitude was even larger than it was in the SO sample, most likely because the B sample was produced from crude and unrefined SO in which the levels of tocopherols, carotenoids and the impurities mentioned above could have been higher. This effect was confirmed by the absorption spectra of SO and B, which are shown in Fig. 4a, and by their fluorescence spectra, which are shown in part (b) of the same figure. Through the absorption spectrum, the region approximately 514 nm had greater absorption in

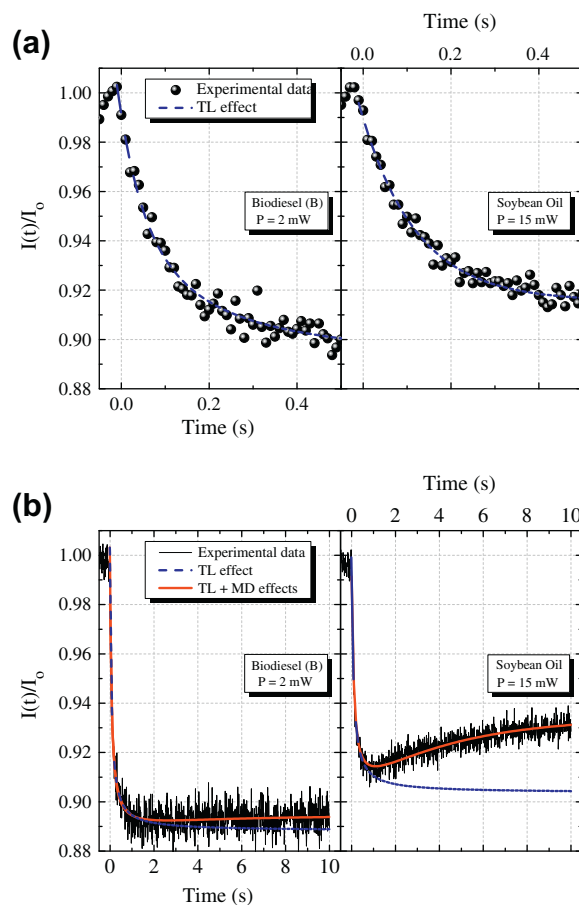
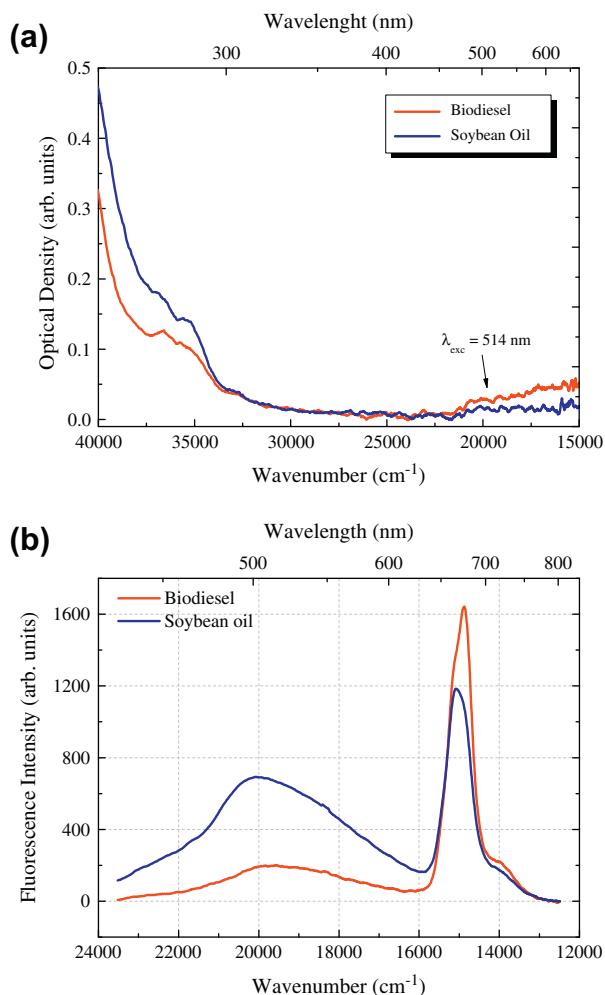


Fig. 3. The thermal lens transient signal for the biodiesel and soybean oil over a short time interval (a) and a long time interval (b). The solid red line is the theoretical curve fit that only considers the TL effect (Eq. (1)); the blue line considers both the TL and mass diffusion effects (Eq. (3)). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

our B sample than in our SO sample. By observing the fluorescence spectra, which were obtained via excitation at 405 nm, it can be noted that the region between 400 and 800 nm was due to the presence of tocopherols,  $\beta$ -carotene and chlorophyll a and b. Because biofuel possesses high levels of chlorophyll, the fluorescence intensity at approximately 680 nm is greater in B than in SO.



**Fig. 4.** UV–V are the optical density spectra (a) and the fluorescence spectra (b) for biodiesel and soybean oil, respectively.

In the UV absorption region, the SO sample exhibited an optical density that was greater than the optical density of the B sample due to the transitions of dienes; these compounds belong to the chromophores group and possess double bonds in the SO molecule, as in the linoleic acid that is present in its chemical composition at the highest percentage (49.7–56.9%). As such, when SO is heated to produce biofuel, the breakup of these double bonds of fatty acids that bind them to other molecules occurs, causing a decrease in the UV absorption region [15].

For long time intervals ( $0.5 \text{ s} < t < 10 \text{ s}$  in Fig. 3b), a divergence between the TL theoretical model (fitted by Eq. (1)) and the experimental data can be observed. This divergence was more pronounced in the SO sample than in the B sample. This effect is related to the concentration gradient that was thermally induced in the sample by the excitation laser beam, and it is called the mass diffusion (MD) effect [16]. In this case, because our analyzed samples were constituted by different molecules, one of them was able to absorb the energy of the excitation laser and the other molecule did not absorb this energy, resulting in a dynamic change in the refractive index of the illuminated volume. In the studied samples, it is thought that the MD effect was mainly due to the triacylglycerol. Approximately 98% of the chemical composition of the SO sample was triacylglycerol, and the concentration of this compound was low in the B sample, which exhibited mono-, di-, tri- and total-acylglycerol percentages of 0.498%, 0.348%, 0.008% and 0.178%, respectively. These values were obtained by a chromatographic

analysis and correspond to approximately 1% of the concentration of the ester.

To write an analytical expression to consider the MD and TL effects in our samples, the theoretical model proposed by Pedreira et al. [17] was considered. It was rewritten as follows:

$$I(t) = I(0) \left\{ 1 - \frac{\theta_{eq} + (\theta - \theta_{eq})e^{-k_d t}}{2} \times \arctan \left[ \frac{2mV}{\left[ (1 + 2m)^2 + V^2 \right] \left( \frac{t_c}{2\tau} + 1 + 2m + V^2 \right)} \right]^2 \right\}. \quad (3)$$

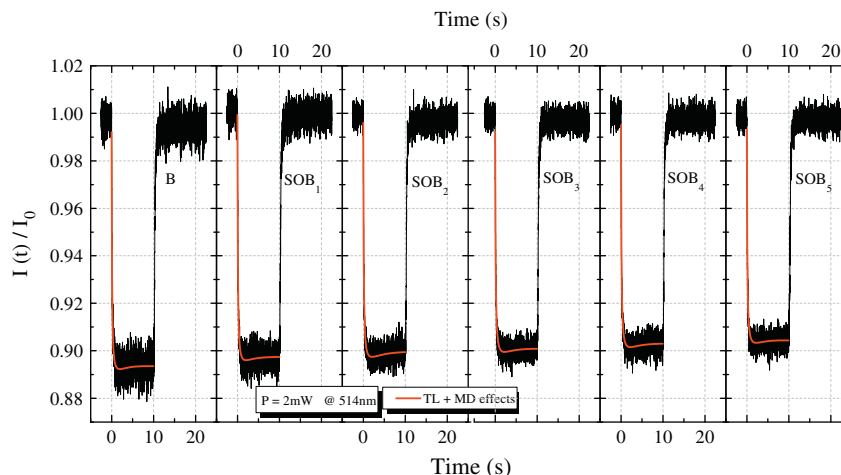
In the above equation,  $\theta_{eq} = \theta \frac{C_{eq}}{C_0}$ , where  $C_{eq}$  is the average concentration on balance and  $C_0$  is the initial concentration of the main absorbers, and  $k_d = \tau^{-1} (\text{s}^{-1})$ , where  $\tau = w_{0e}^2 / 4D_M$  is the time required for the MD effect to occur and  $D_M$  is the mass diffusivity in the sample.

Thus, the transients in Fig. 3b were adjusted by Eq. (3) (the solid red line), where the values of  $\theta$  and  $t_c$ , which were obtained previously by Eq. (1) over a short time interval, were kept fixed. According to the fit, the values for  $\tau$  in the SO and B samples were determined to be  $(0.23 \pm 0.01)$  and  $(8.1 \pm 0.4)$  s, respectively. It is important to note that the values for  $t_c$  and  $\tau$  are considerably different (2–3 orders of magnitude), which suggests that the theoretical model can be used to distinguish the TL and MD effects [17]. Using the values determined by the fit and using the relationships described above, the mass diffusivity was calculated for both SO and B, resulting in the values  $D_M = (22.6 \pm 0.5) \times 10^{-10} \text{ m}^2/\text{s}$  and  $D_M = (6.5 \pm 0.1) \times 10^{-10} \text{ m}^2/\text{s}$ , respectively. The value for SO is roughly 71% higher than the corresponding value for B, indicating that it is a potential parameter to study SOB blends, as will be observed below.

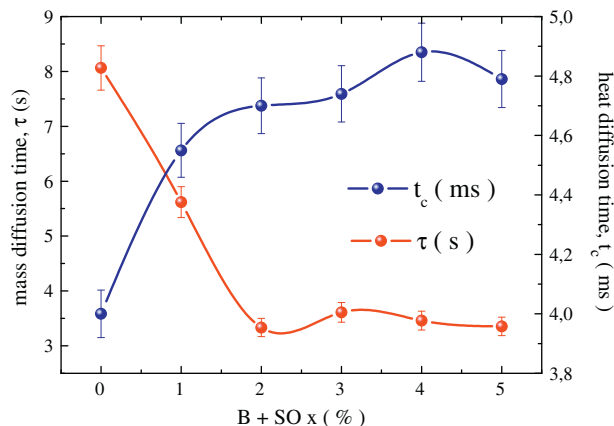
### 3.2. Oil–biodiesel blends

Fig. 5 shows the TL transients for the biodiesel (B) and soybean oil–biodiesel (SOB) blends; these transients were considered when the laser is turned on (from 0 to 10 s) and when the laser is turned off (from 10 to 22 s).

All of the curves were obtained using 2 mW of excitation power, and the curves were plotted at the same scale for the sake of comparison. The TL amplitude signal (from 0 to 0.5 s) decreased from the B sample to the SOB<sub>5</sub> sample, and the MD effect was barely noticeable for these samples. Recently, Malacarne et al. proposed that, if the signal immediately becomes 1 when the laser is turned off, as was the case for our samples, the unexpected TL signal measurement can mainly be attributed to the MD effect [16]. Hence, Eq. (3) was also used to fit all of the experimental curves. The same procedure that was used previously was used again to determine  $\tau$ , i.e. the initial adjustment in a short time interval with Eq. (1) was repeated to obtain  $t_c$ , and the value was maintained in Eq. (3) to obtain the  $\tau$  parameters. The values that were found for  $t_c$  and  $\tau$  are shown in Fig. 6, from which it is observed that, in the sample to which only 2% oil was added to the biodiesel, both  $t_c$  and  $\tau$  assumed values that remained constant as the proportion of oil in the biodiesel as increased to 5%. In other words, between the B and SOB<sub>2</sub> blends, it is possible to note variations of 15% and 59% in  $t_c$  and  $\tau$ , respectively, which are sufficient to distinguish the oil in a given sample of biodiesel. More emphasis can be placed on the  $\tau$  parameter, whose value decreased by 30% when only 1% oil was added to the biodiesel. This parameter proved to be very sensitive in determining the amount of oil level mixed into a given quantity of biodiesel. Another interesting point to note is that the values for  $t_c$  that were determined in the SOB<sub>5</sub> blend are similar to the values found for the SO sample. This finding is an indication



**Fig. 5.** The thermal lens transient signal for biodiesel and oil-biodiesel blends. All curves were obtained using the same excitation power (2 mW) after the samples were placed in a quartz cuvette with a thickness of 1 mm. The solid red lines correspond to the fit with Eq. (3), in which both the TL and the MD effects are considered. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)



**Fig. 6.** The derived values for  $t_c$  and  $\tau$  with respect to the concentration of oil in biodiesel.

that the heat generated in the blend samples flows through the molecules with the greatest size (triacylglycerol), as previously suggested.

From the values of  $\tau$  and  $t_c$  and given that  $w_{oe} = 45.9 \mu\text{m}$ , the mass and thermal diffusivity values were also calculated for the blends. These values are listed in Table 2 with the values calculated in the previous section for the B and SO samples. As expected, the variation in the  $D_{Th}$  and  $D_M$  values was the same in the B and SOB<sub>5</sub>. Moreover, it is interesting to observe that  $D_{Th}$  and  $D_M$  have very different magnitudes, which reinforces our assumption that the TL experimental method is useful for discriminating the heat and mass diffusion effects observed in a similar TL procedure.

**Table 2**  
The thermal diffusivities ( $D_{Th}$ ) and mass diffusivities ( $D_M$ ) of the studied samples.

Sample	$D_{Th}$ ( $10^{-7} \text{ m}^2/\text{s}$ )	$D_M$ ( $10^{-10} \text{ m}^2/\text{s}$ )
B	$1.31 \pm 0.03$	$6.5 \pm 0.1$
SOB <sub>1</sub>	$1.15 \pm 0.02$	$9.4 \pm 0.2$
SOB <sub>2</sub>	$1.11 \pm 0.02$	$15.8 \pm 0.3$
SOB <sub>3</sub>	$1.10 \pm 0.02$	$14.6 \pm 0.3$
SOB <sub>4</sub>	$1.07 \pm 0.02$	$15.2 \pm 0.3$
SOB <sub>5</sub>	$1.09 \pm 0.02$	$15.7 \pm 0.3$
SO	$1.05 \pm 0.02$	$22.6 \pm 0.5$

## 4. Conclusions

In conclusion, the heat and mass diffusion effects that were observed during an experimental TL spectroscopy procedure were used to characterize biodiesel and oil-biodiesel blends, principally because this method allows the determination of the thermal and mass diffusivities. When transitioning from pure biodiesel (B) to the sample with 98% biodiesel and 2% soybean oil (SOB<sub>2</sub>), the thermal diffusivity decreased by 15% and the mass diffusivity increased by 59%, indicating that both parameters can provide significant information about the presence of impurities (oil) in biodiesel. This result suggests that to control the quality of the biodiesel, our methodology may be applied during the transesterification procedure to control the quality of biodiesel by indicating the reaction's efficiency. In addition, the method can be used to indicate the presence of oil as an adulterant in biodiesel solutions.

## Acknowledgements

The authors thank Fundect-MS, CAPES, FINEP and CNPq for their financial support and the Applied Optics Group (GOA) of the Federal University of Grande Dourados (UFGD) for supplying the biodiesel sample.

## References

- [1] Janaun J, Ellis N. Perspectives on biodiesel as a sustainable fuel. *Renew Sust Energy Rev* 2010;14:1312–20.
- [2] Som S, Longman DE, Ramírez AI, Aggarwal SK. A comparison of injector flow and spray characteristics of biodiesel with petrodiesel. *Fuel* 2010;89:4014–24.
- [3] Meher LC, Sagar D, Vidya D, Naik SN. Technical aspects of biodiesel production by transesterification – a review. *Renew Sust Energy Rev* 2006;10:248–68.
- [4] Gerpen JV. Biodiesel processing and production. *Fuel Process Technol* 2005;86:1097–107.
- [5] Knothe G. Analyzing biodiesel: standards and other methods. *JAOC* 2006;83:823–33.
- [6] Monteiro MR, Ambrozini ARP, Lião LM, Ferreira AG. Critical review on analytical methods for biodiesel characterization. *Talanta* 2008;77:593–5.
- [7] Snook RD, Lowe RD. Thermal lens spectrometry – a review. *Analyst* 1995;120:2051–68.
- [8] Castro MPP, Andrade AA, Franco RWA, Miranda PCML, Sthel M, Vargas H, et al. Thermal properties measurements in biodiesel oils using photothermal techniques. *Chem Phys Lett* 2005;411:18–22.
- [9] Lima SM, Figueiredo MS, Andrade LHC, Caires ARL, Oliveira SL, Aristone F. Effects of residue and antioxidant on thermo-optical properties of biodiesel. *Appl Opt* 2009;48:5728–32.
- [10] Ventura M, Simionatto E, Andrade LHC, Lima SM. Thermal lens spectrometry for differentiation of biodiesel–diesel blends. *Rev Sci Instrum* 2012;83:043902-1–5.

- [11] Shen J, Lowe RD, Snook RD. A model for cw laser induced mode-mismatched dual-beam thermal lens spectrometry. *Chem Phys* 1992;165:385–96.
- [12] Lima SM, Sampaio JA, Catunda T, Bento AC, Miranda LCM, Baesso ML. Mode-mismatched thermal lens spectrometry for thermo-optical properties measurement in optical glasses: a review. *J Non-Cryst Solids* 2000;273: 215–27.
- [13] Lima SM, Bannwart ES, Oliveira RG, Andrade LHC, Del Ré PV, Jorge N, et al. Evaluation of the thermal diffusivity of vegetable oils during frying by thermal lens spectrometry. *Eur Phys J – Spec Top* 2008;153:531–34.
- [14] Resolution from the Agência Nacional do Petróleo. Gás Natural e Biocombustíveis (ANP), N° 4 from 02.02.2010. See: <[http://www.nxt.anp.gov.br/nxt/gateway.dll/leg/resolucoes\\_anp/2010/fevereiro/ranp%20-%202010.xml?f=templates\\$fn=document-frame.htm\\$3.0\\$g=\\$x](http://www.nxt.anp.gov.br/nxt/gateway.dll/leg/resolucoes_anp/2010/fevereiro/ranp%20-%202010.xml?f=templates$fn=document-frame.htm$3.0$g=$x)>.
- [15] Scherer MD, Oliveira SL, Lima SM, Andrade LHC, Caíres ARL. Determination of the biodiesel content in diesel/biodiesel blends: a method based on fluorescence spectroscopy. *J Fluoresc* 2011;21:1027–31.
- [16] Malacarne LC, Astrath NGC, Medina AN, Herculano LS, Baesso ML, Pedreira PRB, et al. Soret effect and photochemical reaction in liquids with laser-induced local heating. *Opt Exp* 2011;19:4047–58.
- [17] Pedreira PRB, Hirsch LR, Pereira JRD, Medina AN, Bento AC, Baesso ML. Real-time quantitative investigation of photochemical reaction using thermal lens measurements: theory and experiment. *J Appl Phys* 2006;100:044906.