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Thermal Properties of Jojoba Oil Between 20 °C and 45 °C

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Abstract Vegetable oils have been widely studied as biofuel candidates. Among these oils, jojoba (*Simmondsia chinensis*) oil has attracted interest because it is composed almost entirely of wax esters that are liquid at room temperature. Consequently, it is widely used in the cosmetic and pharmaceutical industries. To date, research on *S. chinensis* oil has focused on to its use as a fuel and its thermal stability, and information about its thermal properties is scarce. In the present study, the thermal effusivity and conductivity of jojoba oil between 20 °C and 45 °C were obtained using the inverse photopyroelectric and hot-ball techniques. The feasibility of an inverse photopyroelectric method and a hot-ball technique to monitor the thermal conductivity, and the thermal effusivity of the *S. chinensis* is demonstrated. The thermal effusivity decreased from 538 $W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$ to 378 $W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$ as the temperature increased, whereas the thermal conductivity remained the same over the temperature range investigated in this study. The obtained results provide insight into the thermal properties of *S. chinensis* oil between 20 °C and 45 °C.

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1 Introduction

Vegetable oils have attracted attention because they are eco-friendly and have many uses [1–4]. Among the different vegetable oils, jojoba oil (*Simmondsia chinensis*) stands out because of its wide range of applications in both the cosmetic and pharmaceutical industries. It is also an outstanding candidate for biofuel use [5,6] because of its long chain monoesters (C_{20} to C_{44}) content [7–11]. The mass fraction of wax esters in *S. chinensis* seeds is 40 % to 50 %, and these are a mixture of esters of carboxylic acids and alcohols [12,13].

Intensive research has been carried out to determine the physicochemical properties of *S. chinensis* oil, motivated by its use as fuel, but its thermal properties have only been studied after transesterification [14–16]. Thus, information about the thermal properties of pure untreated *S. chinensis* oil is scarce. To support the increased use of *S. chinensis* oil in new applications, there is a need for careful analysis of its thermal properties so its behavior can be accurately predicted.

The inverse photopyroelectric (IPPE) technique has shown great potential in the thermal characterization of liquids, in particular for thermal effusivity measurements [17–20]. The IPPE technique is based on the photothermal effect by frequency modulated light and thus heating a pyroelectric (PE) sensor. The PE sensor has as adjacent layer the sample in good thermal contact. Thermal waves due to the modulated light carry thermal information regarding PE sensor and sample. IPPE signal analysis allows the estimation of the thermal effusivity.

The hot-ball (HB) method can be used to determine thermal conductivity in liquids and gels [21–23]. The HB method is based on analysis of the transient evolution of the temperature of a metal ball when a step heating condition is imposed. With known ball properties, ball geometry, and proper calibration, the thermal conductivity of a liquid can be determined when the ball is immersed in a liquid [21]. Analysis of a HB signal is based on assumptions of temperature continuity at the solid–liquid interface, the ball being a hollow sphere of radius R with homogeneous properties, immersion of the ball in a semi-infinite liquid sample, and heat flux continuity boundary conditions at the metal–sample interface. When heat (Q) is released with a step function, the temperature at the sphere surface as a function of time can be expressed as follows [21]:

$$T(t) = \frac{Q}{4\pi\kappa R}\left[1 - \exp\left(\frac{\alpha t}{R^2}\right) erfc\left(\frac{\sqrt{\alpha t}}{R}\right)\right], \tag{1}$$

where κ is the thermal conductivity of the surrounding liquid, α is the thermal diffusivity of the surrounding liquid, Q is the released heat, and *erfc(x)* is the standard complementary error function. The HB method is a simple technique to implement for thermal conductivity measurements on liquids or gels [21–23]. The main limitation of this technique is the quantity of sample required to fulfill the theoretical consideration of a sphere being immersed into a semi-infinite medium.

In the present study, the IPPE and HB techniques were used to accurately measure the thermal effusivity and thermal conductivity of *S. chinensis* oil at different temperatures. These results will increase understanding of the thermal behavior of *S. chinensis* oil.

2 Experimental Apparatus and Procedures

2.1 Materials

S. chinensis oil (98 % purity) was obtained from Productos Industriales IGP de Mexico, Mexico City, Mexico. To prevent changes to the physical properties of the sample, it was stored in a light controlled environment at 23 °C with a relative humidity of 20 %.

2.2 HB Method

Figure 1 shows the experimental setup used for the HB technique. The sample was placed in a glass container with a diameter (30 mm) more than 20 times that of the diameter of the ball. Then, a brass ball (ø 1.2 mm) that contained a resistive heater and a thermistor was immersed in the sample. After maintaining the sample at the desired temperature ($x \pm 0.5$ °C), 5 mW of power was supplied to the ball heater, and changes in the temperature were recorded for 120 s. The obtained signals were fitted using Eq. 1, with the thermal conductivity and diffusivity as fitting parameters. One

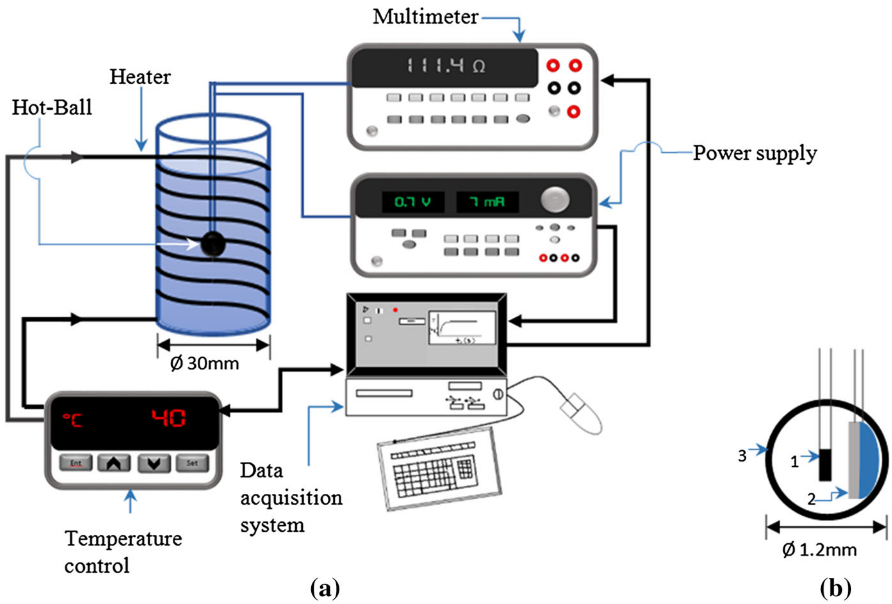

Fig. 1 (a) Hot-ball experimental setup used to obtain the thermal conductivity of the oil sample, (b) detail of the hot-ball sensor. *(1)* Heater, *(2)* thermistor, and *(3)* metal hot-ball

consideration during the experiment was that the temperature applied to the ball was selected to guarantee there was a detectable change in the temperature of the sample. At the same time, it was necessary to avoid convection effects or other influences, such as heat reaching the boundary of the container. To overcome this and other limitations of the standard HB method, more precise results were obtained using the effective ball radius and effective released power techniques. This was achieved using glycerol and distilled water as reference samples with known thermal properties, and using the HB radius and power as fitting parameters for later use in the *S. chinensis* oil measurements.

2.3 IPPE Technique

The photopyroelectric setup (Fig. 2) consisted of a periodically modulated intensity laser beam from a 500 mW, 785 nm solid-state laser (B&W Tek, Newark, DE) that illumined one side of a 500 µm thick slab of lead zirconate titanate (PZT), which acted as the pyroelectric (PE) signal detector. The sample was placed in a temperature controlled container mounted on the other side of the PZT slab, in an IPPE configuration. In this configuration, thermal waves generated by light hitting the PZT surface, diffused through the sensor and the sample.

The measured signal was normalized with a reference signal, which was acquired in advance by keeping the back of the PZT in contact with air [18,24], thus allowing instrumental factors to be taken into account. Because the IPPE mathematical model uses PE thermal properties, those thermal properties were determined beforehand using the open photoacoustic cell method.

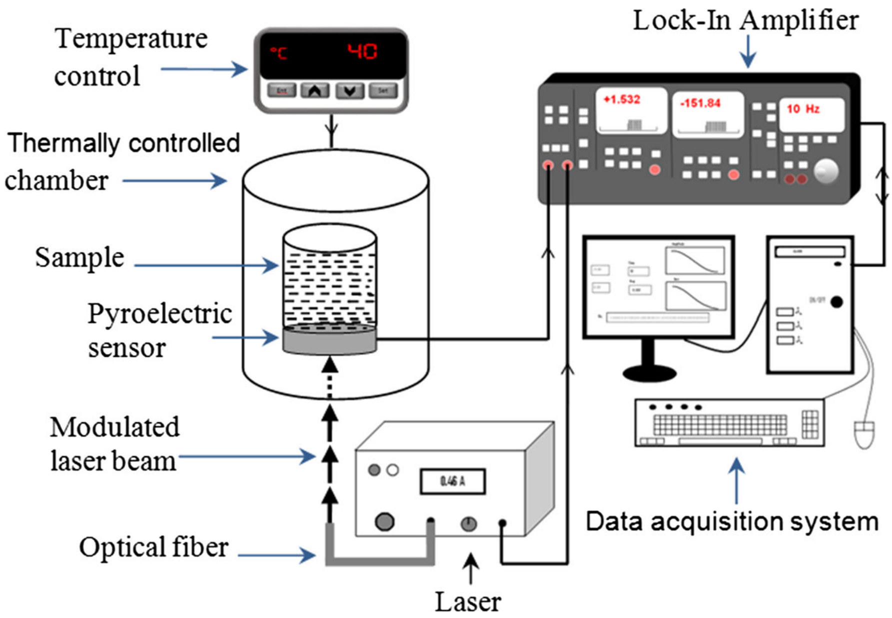

Fig. 2 Experimental setup used to obtain the thermal effusivity of the oil sample

In the proposed configuration, and with the appropriate modulation frequency range, the sample can be considered thermally thick. This means that the thermal diffusion length, defined as $\mu_s = (\alpha_s/\pi f)^{1/2}$, was much shorter than the sample thickness. Then, the normalized signal could be expressed as follows [25]:

$$h(\omega) = C\left[\frac{(1 - e^{\sigma_p l_p})(1 + b) + (e^{-\sigma_p l_p} - 1)(1 - b)}{(g - 1)e^{-\sigma_p l_p}(1 - b) + (1 + g)e^{\sigma_p l_p}(1 + b)}\right], \quad (2)$$

where C is a fitting parameter that is specific to each PE sensor; σ_p is the PE complex thermal diffusion coefficient given by $\sigma_p = (1 + j)/\mu_p$, where $j = (-1)^{1/2}$, $\mu_p = (\alpha_p/(\pi f))^{1/2})$, α_p is the thermal diffusivity of the PE sensor, and f the signal modulation frequency; l_p is the PE thickness; and $b = e_s/e_p$ and $g = e_g/e_p$, where e_s, e_g, and e_p are the thermal effusivities of the sample, air, and PE sensor, respectively.

The frequency range used to perform the scan must be chosen in such a way to ensure that the sample thermal diffusion length is less than the sample thickness. For the current study, this condition was fulfilled at low frequencies (0.1 Hz to 10 Hz). When recording measurements, the chamber temperature was kept at the desired temperature using a commercial temperature controller with a platinum resistor placed in the liquid.

3 Results and Discussion

The thermal conductivity and effusivity of *S. chinensis* oil were measured from 20 °C to 45 °C using the HB and IPPE techniques, respectively. The thermal conductivities were calculated using the thermal conductivity as a fitting parameter in Eq. 1. With

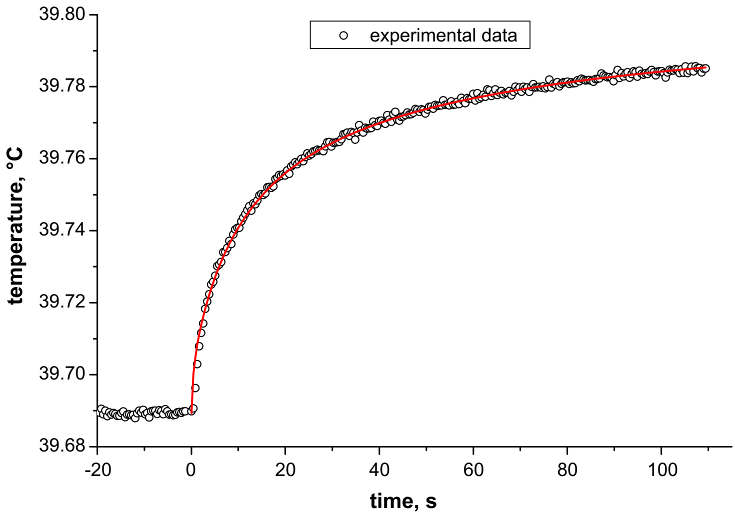

Fig. 3 Hot-ball transient heating measurements. The *solid line* represents the line of best fit using thermal conductivity as the fitting parameter in Eq. 1

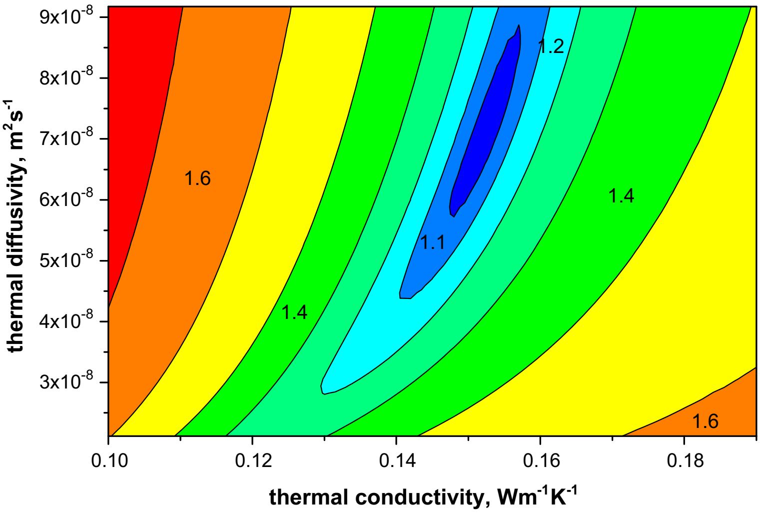

Fig. 4 Contour plot of fitting parameters of the error cost function obtained by considering thermal conductivity and thermal diffusivity as fitting parameters. This confirms the absence of pairwise fitting degeneracy and results in larger uncertainty in thermal diffusivity values when compared with thermal conductivity uncertainty

this equation, it is also possible to obtain the thermal diffusivity from the section where the temperature increases exponentially, which was observed shortly after initiation of heating. Using this method, there was only a slight increase in experimental uncertainty of around 5 %. The temperature evolution in the HB experiments is presented in Fig. 3. Using the least squares method to fit Eq. 1 to the experimental data does not guarantee that fitted pairs of values (thermal effusivity and thermal diffusivity) are the only ones that minimize the error. A multifold degeneracy exists when there are multiple minimum pairs (e.g., a threefold degeneracy), and this should be dealt with by performing a most squares fitting analysis [26].

A contour plot (Fig. 4.) of the fitting parameters based on an error cost function was obtained by considering the thermal conductivity and thermal diffusivity as the fitting parameters. This confirmed the absence of pairwise fitting degeneracy and allowed for a larger uncertainty to be determined for thermal diffusivity, when compared with thermal conductivity.

The HB method is suitable for liquid samples as long as there is enough sample to ensure that the heat released does not reach the sample container. Also, samples with high thermal conductivity need higher values of heat released, leading to convection problems, and increasing the measurement uncertainty. This method is suitable for measuring the thermal conductivity of vegetable oils.

The thermal effusivities were obtained by fitting Eq. 2 to experimental data from the IPPE, using thermal effusivity as the fitting parameter. Examples of the frequency dependencies of the IPPE signal amplitude and phase at 20 °C are shown in Fig. 5, and the obtained effusivities are depicted in Fig. 6.

The fitted thermal parameters of *S. chinensis* oil as a function of temperature obtained by the HB technique are shown in Fig. 6. Generally, the obtained thermal

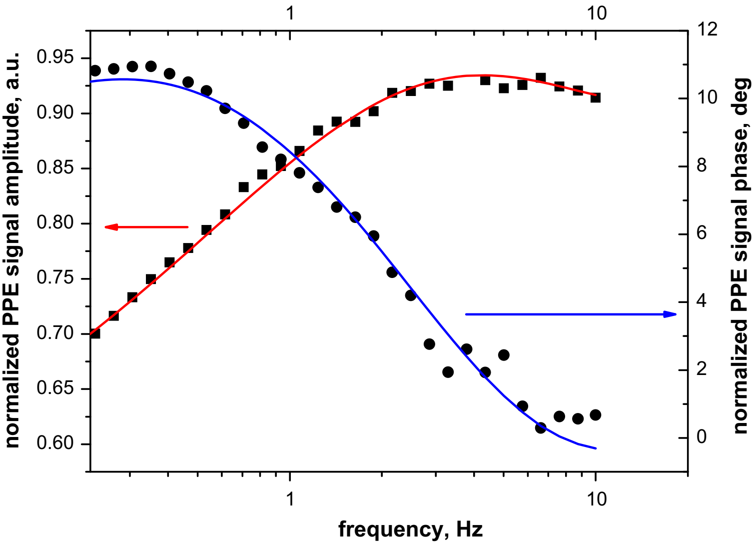

Fig. 5 IPPE normalized amplitude and normalized phase as a function of the light modulation frequency. *Dots* represent the experimental data, and *solid lines* are the lines of best fit for *S. chinensis* oil at 20 °C

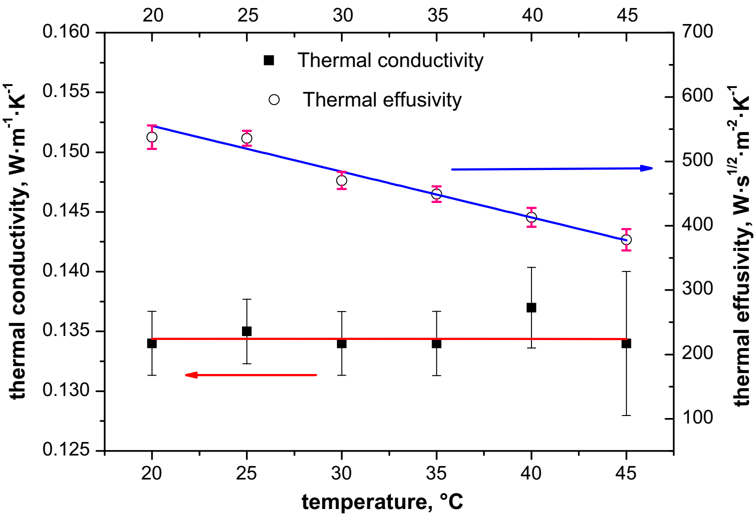

Fig. 6 Thermal effusivity and conductivity of *S. chinensis* oil as a function of temperature. *Dots* represent the experimental values, and *solid lines* are included as a visual guide

conductivity remained constant at around $0.134\,\mathrm{W \cdot m^{-1} \cdot K^{-1}}$ with an error of $\pm 7\,\%$ within the temperature range studied. This thermal conductivity was similar to that for other vegetable oils in the literature, such as olive oil [20].

The thermal effusivity obtained at room temperature was similar to the values reported for avocado and corn oils at the same temperature [27]. Figure 6 shows that thermal effusivity decreased from 538 $W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$ to 378 $W \cdot s^{1/2} \cdot m^{-2} \cdot K^{-1}$ (uncertainty $< 5\,\%$) as the temperature increased. Based on these effusivity values, we believe that the effusivity decreases mainly because the density of the oil decreases.

4 Conclusions

The thermal effusivity and conductivity of *S. chinensis* oil are similar to the values for other vegetable oils. The measured thermal conductivity remains constant within the measurement uncertainty, even though the error tends to increase as the temperature increases. This could be caused by a combination of convection problems because of the sample temperature and the intrinsic error in the fitting process. There is the potential to use two different methods (HB and IPPE techniques) to reduce the error in thermal diffusivity measurements with the HB technique. This paper did not focus on all the possibilities of the HB technique for characterization. Therefore, an error analysis on similar liquids falls outside the scope of this article. Coupling of the HB and IPPE methods is an interesting challenge for the future.

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