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Temperature dependence of thermal conductivity of vegetable oils for use in concentrated solar power plants, measured by 3omega hot wire method

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ABSTRACT

Following the growing need for innovative heat transfer fluids in concentrated solar power (CSP) plants, the thermal conductivities of different vegetable oils (rapeseed, soybean, sunflower, palm, copra, cotton and jatropha) were measured in the temperature range from ambient to 230 °C relative to a reference oil. The small differences in the obtained thermal conductivities are influenced by the fatty acid composition. For balanced saturated/unsaturated fatty acids composition, the average thermal conductivity decreases from 0.167 W m^{-1} K^{-1} at 20 °C to 0.137 W m^{-1} K^{-1} at 230 °C. The use of a reference synthetic oil makes the calibration of the thermal probe unnecessary. The used method is based on a hot wire thermal probe with ac excitation and 3ω lock-in detection and has a long-term relative error of 1.2% and absolute accuracy of 2%. It allows measuring in real-time, continuously and independently, the thermophysical properties of oils for thermal applications.

1. Introduction

High temperature oils are widely used as industrial heat transfer fluids in many process applications including concentrated solar power (CSP) plants [1]. Most of commonly used thermal fluids are suitable for a wide range of temperatures. However, mineral or synthetic oils are petroleum-based and have a tendency to resource depletion. Synthetic organic fluids and mineral oils are considered to be very expensive (6€/L) and hazardous due to the degradation by-products [2]. In the perspective of sustainable development, it is necessary to establish a set of safe and non-toxic thermal oils for use in CSP plants. Vegetable oil as heat transfer fluid is a promising solution. A real and growing need for this innovative fluid is to determine the thermal properties from ambient temperature to 230 °C, among which the thermal conductivity k. No published data are available in the literature on the thermal conductivity of vegetable oils in this temperature range. Usually, vegetable oils were considered as food materials and their thermal conductivities were measured only for the food processing purpose. Few researches were carried about for this important thermal property in relation to this utilization [3–9]. However, not many kinds of vegetable oils were investigated and the temperature range rarely exceeded 100 °C while their composition was usually not given.

Over the years, different techniques have been adopted for experimental studies on the thermal conductivity properties of liquids [10]. Accurate measurement of k is especially difficult. The main challenges are to inhibit the heat transfer by convection in the liquid volume and to control the evolution of temperature gradients during the measurements. The most common traditional techniques are the steady-state methods, the temperature oscillation method [11] also known as modified Ångström method, the transient hot-wire (THW) method with resistive or thermocouple temperature measurement [12], the flash method and various acoustic, photothermal and light scattering methods [13–15]. The

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Nomenclature

f	frequency, Hz
F	form factor
I	current intensity, A
k	thermal conductivity, W m^{-1} K^{-1}
$2l$	wire length, m
R	electrical résistance, Ω
r_p	wire radius, m
T	temperature, °C
t	time, s
T_c	critical temperature, °C
SS_{res}	residual sum of squares
SS_{tot}	total sum of squares

Greek symbols

α	thermal diffusivity, m^2 s^{-1}
β	temperature coefficient of R, K^{-1}
μ	thermal diffusion length, m
ρ	electrical resistivity, Ω m
θ	temperature oscillation, K
ω	angular frequency, rad s^{-1}

Indexes and exponents

p	probe
r	reference
Re, Im	Real and Imaginary parts

THW technique has been widely used for obtaining standard reference data for the thermal conductivity of fluids [16] and also for gases and solids. A method similar to the THW is the one called "3ω" suggested by Cahill in 1987 [17]. The 3ω hot wire (3ωHW) method can be applied to liquids [18] and gases [19] as well. The main difference from the THW relies in the frequency-domain modulation instead of the time-domain modulation. With 3ω, a sinusoidal current at frequency ω passes through the wire and generates a heat source at frequency 2ω. The corresponding temperature oscillation is retrieved by the voltage component at 3ω, resulting from mixing the current at 1ω with the electrical resistance at 2ω.

In response to growing need for innovative heat transfer fluids, the thermal conductivity of different vegetables oils was measured in a broad temperature range. Given the fact that the aim of the present study was to perform temperature-dependent measurements, and having available a well-characterized synthetic oil, it seemed judicious to opt for a relative 3ωHW measurement procedure at fixed frequency with real-time data acquisition and lock-in signal detection. Relative measurements avoid calibrating the temperature response of the probe in the whole investigated temperature range. Moreover, various sources of errors are efficiently canceled if the reference and unknown samples have similar properties.

2. Theoretical background

The thermal probe (ThP) used is considered as a metallic wire of length $2l$ and radius r_p totally immersed in the fluid to be analyzed, excited by an ac current $I(t) = I_0 cos(\omega t)$. The wire temperature $\theta(f,t)$ has a 2ω component proportional to the power $I^2(t)R_0$. For a sufficiently long wire, $\theta(f,t)$ can be considered uniform in the axial direction. For a liquid sample that is thermally more insulating than the probe wire material, the temperature within the wire is uniform also in the radial direction ($k_p/k > 500$ in our case). At low frequency (below the kHz for the thermal probe used), the thermal energy stored by heat capacity c_p in the wire is negligible and it is possible to consider that all the power is totally dissipated by radial conduction within the fluid. The term depending on 3ω is generated by nonlinear mixing of the excitation current at ω with the electrical resistance change (due to temperature oscillation) at 2ω. The 3ω signal value depends on the average temperature distribution along the wire, in a cylindrical geometry. For a periodic line heat source in an infinite and homogeneous medium, the dimensionless temperature profile can be expressed as a dimensionless form factor F [20]:

$$F = \frac{k_p}{k}\left(\frac{r_p}{l}\right)^2 \frac{1}{2}\left(\ln\frac{\mu}{1.2594 r_p} - j\frac{\pi}{4}\right) \tag{1}$$

where $\mu = [\alpha\pi^{-1}(2f)^{-1}]^{1/2}$ is the thermal diffusion length in the medium at thermal frequency $2f$. Eq. (1) is equivalent to the thermal impedance of the liquid seen at the wire-liquid interface normalized to the thermal resistance of the half-length wire in the axial direction, considering the end supports as infinite heat sinks. If $F << 1$ the wire is thermally long and heat loss to end supports can be neglected. In the experimental conditions described in Section 3, $F \approx 10^{-3}$. The last factor in parentheses is in fact an approximation valid for $r_p/\mu << 1$ (at low frequency) by keeping the first term in the series development of the zeroth-order modified Bessel function [21]. This approximation is justified in Section 3. While Re(F) decreases with increasing frequency, Im(F) is constant, but it has lower value than Re(F).

The magnitude of F factor (and therefore the 3ω signal amplitude) is inversely proportional to the sample thermal conductivity k. In order to separate the corresponding contributions of conductivity and diffusivity to F, only the imaginary part Im(F) will be used to monitor the evolution of k of a liquid as a function of temperature [18]:

$$k(T) = k_r(T)\frac{\mathrm{Im}(F_r)}{\mathrm{Im}(F)} \tag{2}$$

According to Eq. (2), the thermal conductivity of a fluid can be calculated using the conductivity of a reference fluid and the imaginary parts of the two signals. On the other hand, the phase of Eq. (1) yields the α value at fixed frequency. The result depends only on r_p without the need for other calibration.

3. Experimental

The thermal probe used in the present work consists of a Nickel wire having the characteristics of Table 1. The most important one

Table 1
Properties of the thermal probe.

r	20 μm
l	19 mm
c	3.95·10^6 J m^{-3} K^{-1}
k_p	90.9 W m^{-1} K^{-1}
ρ	6.91·10^{-8} Ω m
β	5.19·10^{-3} K^{-1}
R	1.05 Ω