Physical Properties of Liquid Edible Oils

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ABSTRACT: Literature values of density, viscosity, adiabatic expansion coefficient, thermal conductivity, specific heat (constant pressure), ultrasonic velocity, and ultrasonic attenuation coefficient are compiled for a range of food oils and water at 20°C, and a series of empirical equations are suggested to calculate the temperature dependency of these parameters. The importance of these data to the application of ultrasonic particle-sizing instruments to food emulsions is discussed.
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Edible oils extracted from plant and animal sources are important in foods and various other industries (e.g., cosmetics, pharmaceuticals, lubricants). They are key components of the diet and also provide characteristic flavors and textures to foods. During extraction, purification and usage, oils undergo a variety of processing operations, including frying, distillation and chemical modification which may alter their properties. However, prediction of the behavior of oils under real processing conditions from molecular properties is beyond current understanding. Instead, semi-empirical equations are developed that relate the property of interest (e.g., time for fat to drain from a fried potato chip) to independently measurable bulk properties (e.g., density, viscosity, and surface tension). With these equations, it is possible to predict how changes in the properties of an oil alter the efficacy of a process without resorting to time-consuming trial-and-error experiments. The physical properties of edible oils depend primarily on composition (and hence on biological origin) and temperature. In the current work, we have compiled selected bulk parameters for oils in terms of these variables.

Additionally, emulsions that contain edible oils are important in many foods (e.g., milk, salad dressings, ice cream, margarine) (1). In these foods, many of the oil droplets are too small (<1 µm) to be readily observed by light microscopy and too concentrated ($>1\%$) to be characterized by light scattering. Development of new technologies to characterize food emulsions would be extremely valuable for product development and quality control. A promising approach to this problem is the use of ultrasound (2–5; McClements, D.J., and J.N. Coupland, submitted for publication). A range of commercial instruments has recently become available to measure ultrasonic velocity and/or attenuation spectra for liquids. These spectra can be converted to droplet size distributions by using ultrasonic scattering theory (2,4). Interpretation of the spectra requires detailed information about the physicochemical properties of the component phases, specifically, ultrasonic velocity (c), attenuation (α), specific heat at constant pressure (Cp), density (ρ), adiabatic expansion coefficient (B), viscosity (η), and thermal conductivity (τ). At present, the application of ultrasonic particle-sizing technologies to food emulsions is limited because the physicochemical properties of many edible oils are not tabulated. For this reason, we present a compilation of the relevant parameters for a range of common food oils. We start by compiling available measured values at a single temperature (20°C) and then consider various functions that can be used to estimate temperature dependency.

Physical properties of oils at 20°C. The relevant parameters are compiled from a variety of literature sources in Table 1. When available, data cited represent a real measurement at 20°C. Extrapolations are used only when data are available above and below this temperature. Exceptions to this rule are noted in the table. Similar physical parameters are also compiled for water as a comparison. To a first approximation, the aqueous phase of an emulsion can be assumed to be equivalent to pure water, and these data may be helpful in interpreting ultrasonic spectra of an emulsion.

Temperature dependence of food oil properties. The following equations are used to model the temperature dependency of the physical properties of oils:

$$c = c_0 + c_1 T \qquad [1]$$

$$\rho = \rho_0 + \rho_1 T \qquad [2]$$

$$Cp = Cp_0 + Cp_1 T \qquad [3]$$

$$\eta = \eta_0 \exp[-\eta_1/k(T + 273.13)] \qquad [4]$$

where subscripted terms are constants, T is temperature (°C), and k is the Boltzmann constant. These equations have been

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TABLE 1
Physical Properties of Liquid Edible Oils at 20°C

Oil	c (m·s^{-1})	α (Np·m^{-1}) (2 MHz)	Cp (J·kg^{-1}·°C^{-1})	ρ (kg·m^{-3})	η (mPa·s)	B (×10^{-4}·°C^{-1})	τ (W·m^{-1}·°C^{-1})
Water^{6}	1482.7^{7}		4.176	998.2	1.00	2.07	0.604
Sunflower	1471.6^{8}		2.197^{11,c}	919^{16}	47^{i}	6.61^{16}	
Corn	1469.5^{8}		1.956^{12,c}	920^{17,f}	64.5^{i}	7.22^{17,f}	
Olive	1464.0^{8}	6.5^{9,b}	1.895^{11,c}	915.8^{18}	92.0^{i}		0.166^{22}
Rape	1468.4^{8}	3.6^{9,b}	1.834^{11,c}	911.4^{17,f}	73^{19,f}	7.19^{17,f}	0.160^{23}
Cotton			1.916^{13,d}	918.7^{18}	51^{18,g}	7.30^{21}	0.172^{13,d}
Peanut	1465.9^{8}	6.0^{9,b}		913^{16}	74^{i}	6.52^{16}	0.17^{23,h}
Palm	1459.3^{8,a}		2.000^{14}	919^{18}	85^{14}		
Safflower	1471.4^{8}	4.0^{9,b}		922.0^{9,b}		65^{i}	
Soy	1469.8^{8}	4.9^{10}	1.917^{15,e}	922.8^{17,f}	59^{19,f}	7.24^{17,f}	

[a] Extrapolated from 50°C. Note: Values shown are either reported directly from the literature source cited or extrapolated from adjacent temperatures. Superscripted numbers indicate reference for data.
[b] Recorded at 19.4°C.
[c] Extrapolated from 70°C.
[d] Recorded at 25°C.
[e] Recorded at 19.7°C.
[f] Extrapolated from 23.9°C.
[g] Extrapolated from 37.8°C by using correlation from Reference 22.
[h] Recorded at 33°C.
[i] Coupland, J.N., and D.J. McClements, submitted for publication.

successfully applied to food oils (8,17,18; Coupland, J.N., and D.J. McClements, submitted for publication). The thermal expansion coefficient is by definition: $B = -(\partial \ln\rho/\partial T)_P$ (6); so, its temperature dependency can be calculated from the constants given for the density correlations. Values for the constants in equations 1–4 were calculated from published measurements and are listed in Table 2. Thermal conductivity and ultrasonic absorption coefficient are discussed separately below. Complementary equations for the properties of water are listed in the Appendix section. There is relatively little variation in the properties of different oils; thus, average values from Table 2 are used to calculate the values for a typical food oil for comparison with water in Figure 1.

An alternative series of empirical relationships for oils was developed by Choi and Okos (30), who measured the temperature dependency of thermal conductivity, thermal diffusivity, density, and specific heat for a group of food oils (milk fat, vegetable oil, lard, and corn oil) and developed a series of generic equations for "fat." These equations provide valuable approximations but should be treated with caution because the predictions can deviate substantially from observations published elsewhere.

DISCUSSION

Few materials are as well characterized as water; consequently, the data available (see the Appendix section) are of high quality. On the other hand, food oils often exhibit significant variations in their composition; consequently, it is impossible to define unique values for any oil. None of the data reported here represent a survey of the range of measured parameters for all varieties of a particular oil; so, the degree of interspecies variability remains undefined. An estimate may be obtained by considering the relatively low variation (±1.5% at 50°C) (31) in reported density for palm oil from

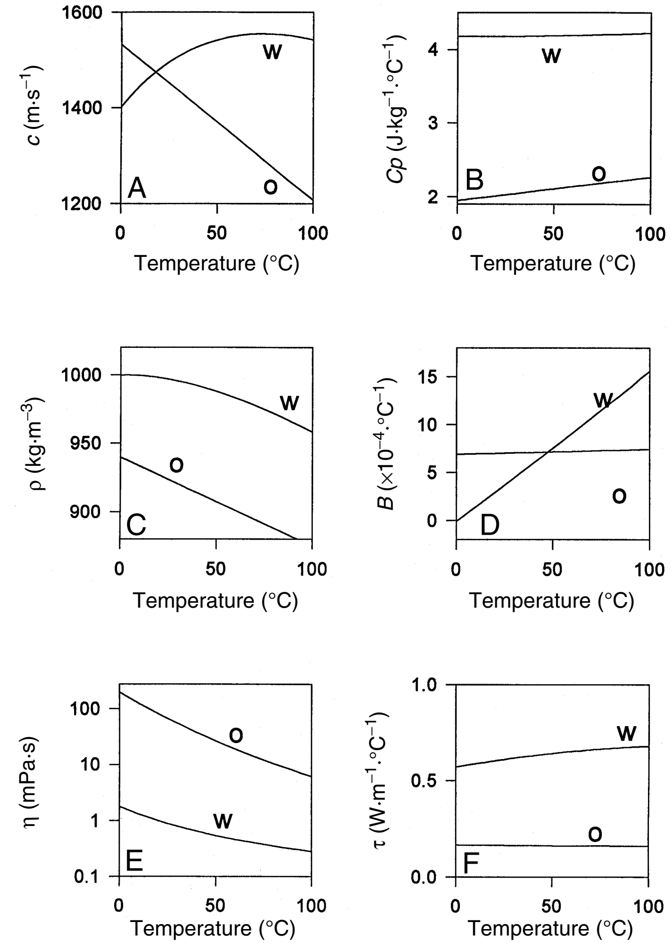

FIG. 1. Temperature dependence of the thermophysical properties of water (w) and an average vegetable oil (o). (A) Ultrasonic velocity C, (B) specific heat C_p, (C) density ρ, (D) thermal expansion coefficient B, (E) viscosity η, and (F) thermal conductivity τ. Data are calculated from Equations 1–8 by using average data from Table 2, data from Table 4, and values given in the text.

TABLE 2
Empirical Constants to Predict the Physical Properties of Liquid Edible Oils

	ρ_0 (kg·m^{-3})	ρ_1 (kg·m^{-3}·°C^{-1})	ln η_0	η_1 (kJ·mol^{-1})	c_0 (m·s^{-1})	c_1 (m·s^{-1}·°C^{-1})	Cp_0 (J·kg^{-1}·°C^{-1})	Cp_1·10^3 (J·kg^{-1}·°C^{-1})	Reference	T (°C)	n	r^2
Coconut	937.16	–0.70							17	37.8–110	6	1.000
Coconut			–14.91	29.44					14	25–50	6	0.999
Coconut			–13.53	25.66					19	38.7–110	6	0.997
Coconut	1069.75	–0.71							16	20–80	7	0.955
Corn	934.23	–0.65							17	23.9–110	7	0.998
Corn			–13.80	27.18					[d]	5–90	90	0.998
Corn			–13.45	26.09					19	23.9–110	7	0.979
Corn					1532.4	–3.23			8	20–70	36	0.999
Corn					1533.5	–3.2			28	20		
Cottonseed[a]							1.93	2.55	18	15–60		
Cottonseed							1.86	4.18	13	25–45	3	1.000
Cottonseed[b]							1.99	2.30	18	40–70		
Cottonseed[c]							1.92	4.06	18	60–80		
Crambe	923.00	–0.67							17	23.9–110	7	0.999
Grapeseed					1533.9	–3.24			8	20–70	36	0.999
Grapeseed					1534.7	–3.2			28	20		
Lesquerella	955.69	–0.67							17	23.9–110	7	0.999
Milk fat			–13.01	24.66					25	37–70	9	0.991
Milkweed	935.52	–0.68							17	23.9–110	7	0.999
Olive			–14.35	29.12					[d]	5–90	90	0.998
Olive					1528.9	–3.23			8	20–70	36	0.999
Olive					1531	–3.3			28	20		
Palm					1515	–3.1			8	50–70	10	0.999
Palm							1.97	3.05	14			
Palm kernel			–14.88	29.60					14	30–50	5	0.999
Palm olein			–14.93	30.35					14	20–50	7	0.996
Peanut			–14.22	28.59					[d]	5–90	90	0.999
Peanut			–12.69	24.55					10	20–60	4	0.999
Peanut					1528.9	–3.23			8	20–70	36	0.999
Peanut					1529.9	–3.2			28	20		
Peanut	927.13	–0.60							16	0–80	9	0.991
Peanut							2.06	1.67	18	27–57		
Peanut[b]							1.97	4.89	18	47–77		
Rape	923.05	–0.66							17	23.9–110	7	1.000
Rape			–13.26	26.26					19	23.9–110	7	0.996
Rape			–12.92	24.85					10	20–60	5	0.998
Rape			–13.16	24.60					26	2.5–100	25	0.986
Rape			–13.57	26.68					[d]	5–90	90	0.999
Rape					1532.9	–3.24			8	20–70	36	0.999
Rape					1533.4	–3.2			28	20		
Rice bran	931.42	–0.60							16	0–80	9	0.992
Safflower					1534.4	–3.24			8	20–70	36	1.000
Safflower			–14.80	29.50					[d]	5–90	90	0.998
Safflower			–11.76	21.80					10	20–60	5	0.991
Safflower					1535.4	–3.2			28	20		
Seal	930.38	–0.64							24	5–55	6	0.973
Seal					1533.16	–3.09			24	5–55	6	0.988
Seal			–16.57	34.70					24	15–55	9	0.984
Sesame			–14.10	28.16					[d]	5–90	90	0.997
Soy	934.41	–0.67							17	23.9–110	7	1.000
Soy					1536.2	–3.29			8	5–70	30	0.999
Soy					1537.8	–3.4			28	20		
Soy							1.87	3.0	15	1–100	8	0.990
Soybean			–13.63	26.46					14	20–50	7	0.999
Soybean			–12.96	24.64					19	23.9–110	7	0.997
Sperm whale	884.53	–0.65							24	5–55	6	0.987
Sperm whale					1528.5	–3.59			24	5–55	6	0.965
Sperm whale			–14.40	27.62					24	15–55	9	0.987
Sunflower					1538	–3.28			8	5–70	30	0.999
Sunflower			–13.83	27.17					[d]	25–50	90	0.998

(continued on next page)

TABLE 2 *(continued)*

	ρ_0 (kg·m^{-3})	ρ_1 (kg·m^{-3}·°C^{-1})	ln η_0	η_1 (kJ·mol^{-1})	c_0 (m·s^{-1})	c_1 (m·s^{-1}·°C^{-1})	Cp_0 (J·kg^{-1}·°C^{-1})	$Cp_1 \cdot 10^3$ (J·kg^{-1}·°C^{-1})	Reference	T (°C)	n	r^2
Sunflower			−22.89	43.74					27	25–50	6	0.998
Sunflower					1537.6	−3.3			28	20		
Sunflower	933.76	−0.61							16	20–80	11	0.995
Sunflower[b]			−22.79	42.23					27	25–50	6	0.999
Vegetable					1537.0	−3.4			28	20		
Average values	940.00	−0.65	−14.60	28.48	1532.18	−3.25	1.90	5.9				

[a] The relevant equations (1–4) are described in the text. Partially hydrogenated.
[b] Hydrogenated.
[c] Highly hydrogenated.
[d] Coupland, J.N., and D.J. McClements, submitted for publication.

various geographical sources. In the absence of more detailed information, it is reasonable to use this level of accuracy for all data reported here.

A sample of oil may undergo various physical and chemical changes during storage, such as crystallization and oxidation. Crystallization becomes thermodynamically favorable when an oil is cooled below its melting point. Nevertheless, crystallization will only occur once stable nuclei are formed in the liquid oil. In bulk oils, only a small degree of supercooling is required to form stable nuclei because of the presence of impurities. In emulsified oils, a much greater degree of supercooling is required (typically 10–15°C) before crystallization is observed because the probability of finding an impurity in an emulsion droplet is extremely small. Therefore, crystallization relies on homogeneous nucleation (32). There are relatively few data compiled for solid fats, and this data compilation is confined to liquid oils. However, at low temperatures, these data should be treated with caution because a small proportion of solid fat will cause significant changes in the physical properties of the oil.

Most food oils contain components that are capable of reacting with oxygen. The most important are the reactions of polyunsaturated fatty acids, which oxidize to form a rancid odor. It is possible to correlate bulk properties of oils with some measurements of oxidation [for example, the specific heat and density of palm oil decrease with degree of unsaturation (14)]. Only a small proportion of an oil needs to be oxidized before a food becomes organoleptically unacceptable. On the other hand, fairly large alterations in composition are required to cause significant changes in most bulk properties. So, it seems reasonable to neglect the effects of oxidation on the physical properties of edible oils (surface tension is a probable exception to this rule). The oxidation behavior of emulsified oils is frequently different to similar oils in bulk (33).

*Ultrasonic properties***.** At relatively low ultrasonic frequencies ($f < 10$ MHz), most fully liquid oils behave as isotropic fluids, and their velocities are frequency-independent. The oils listed in the present work are all assumed to behave in this manner. Empirical relations are available to predict the ultrasonic velocity of oils from their fatty acid composition (8). Deviation from this behavior is a sensitive probe for supramolecular lipid structure. In studies of this type, ultrasonic velocity measurements are often used to calculate adiabatic compressibility ($= 1/c^2\rho$). Ultrasonic velocity in the component phases is one of the most important variables in predicting the velocity of sound in an emulsion, and even the slight variation reported here would lead to considerable differences between spectra. Fortunately, many of the instruments designed for ultrasonic particle sizing can also be used to measure the ultrasonic velocity of a pure liquid. So, it will often be unnecessary to rely on published data. The speed of sound in water has a maximum at approximately 75°C, while that of oils decreases monotonically with temperature. The speed of sound in oil is equivalent to that in water at approximately 20°C.

The ultrasonic attenuation coefficient is a measure of how much ultrasound is dissipated in an oil per unit distance. The attenuation coefficient has little direct value beyond predicting the ultrasonic properties of an emulsion. However, in this application, a precise value is essential, and direct measurement is obviously the preferred method. The attenuation coefficient increases with frequency, at a single temperature, which is usually expressed as a power law function: $\alpha = \alpha_0 \cdot f^{\alpha_1}$, where f is frequency (MHz). Typical values of α_0 and α_1 at 19.4°C are 1.0–1.9 and 1.7–1.8, respectively (9) (castor oil has a much higher attenuation, $\alpha_0 = 11.0$). Attenuation and its frequency dependence tend to decrease with increased temperature, and the power law relationship may no longer be appropriate (10) and predictions of $\alpha(f,T)$ cannot be made to adequate precision. If direct measurements are not available, some data sources are suggested in Table 3.

Specific heat. Specific heat is a measure of the energy required to raise the temperature of a unit mass of material. It is believed to be largely independent of the molecular weight for oils, but it does increase with unsaturation (14). The values for oils are less than half that of water. The specific heat of oils has often been observed to increase linearly with temperature (13,18), and this approach is used to model the data presented here. Other workers have observed nonlinear increases at higher temperatures ($T > 70$°C) (11,12); however, this may be due to autoxidation reactions. The specific heat of water has a minimal value at approximately 8°C and increases slightly at higher or lower temperatures.

TABLE 3
Literature Sources for Temperature and Frequency (*f*) Dependence of Attenuation Coefficient for Edible Oils

Oil	*f* (MHz)	*T* (°C)	Reference
Safflower, soy, peanut, rape	0.5–18	0–60	10
Sperm whale, seal	1.5–60	5–55	24
Castor, olive, peanut, safflower, rape	2–95	19.4	9
Coconut	1–5	20–25	35
Olive	1–5	25–60	36
Olive, castor	3.15, 3.95	0–55	37

Density and thermal expansion coefficient. The density of a material is a measure of the mass per unit volume. The density of most food oils is less than that of water. In general, the density of an oil decreases with molecular weight and increases with unsaturation (14). Several workers (many citations are provided in Ref. 34) have developed empirical functions to relate vegetable oil density to fatty acid composition and temperature. The density of water has a maximum at approximately 4°C and then decreases with further increases in temperature. The density of oil decreases linearly with temperature.

The thermal expansion coefficient defines the fractional changes in the volume of a material with temperature. Its value increases approximately linearly with temperature for liquid oils. The thermal expansion coefficient of water is zero at the density maximum (~4°C) and increases approximately linearly on either side of this value. The thermal expansion coefficients of water and oil are equal at approximately 40°C.

Viscosity. Viscosity is a measure of intermolecular friction in a fluid and hence of its resistance to flow. Food oils behave as ideal Newtonian liquids over a wide range of shear rates and therefore may be characterized by a single viscosity. Viscosity of oils decreases exponentially with increasing temperature, which is modeled here by an Arrhenius-type equation. More complex polynomial equations have been developed for specific samples (26), but intersample variability means that the enhanced precision implied is generally unjustified. The viscosity of water is much less (~2%) than that of most oils (Fig. 1).

Thermal conductivity. Thermal conductivity describes the ease with which heat passes through a material. It is a particularly difficult parameter to measure, and consequently there are few values reported for food oils. A tabulation (23) of largely single-temperature measurements (made between 4 and 35°C) reported values of $\tau = 0.156$–$0.176\ \mathrm{W{\cdot}m^{-1}K^{-1}}$ (mean 0.167, $\sigma = 0.008$, $n = 9$) and no apparent dependency on temperature. Similar data for cottonseed oil were obtained at 25°C, $\tau = 0.172\ \mathrm{W{\cdot}m^{-1}K^{-1}}$ (13). Kaye and Higgins (22) showed that thermal conductivity of olive oil decreases slightly in a linear manner with temperature (0–200°C): $\tau = 0.1676 - 6.00 \times 10^{-5}T$, $n = 11$, $r^2 = 0.999$. In the absence of more complete information, it is reasonable to accept this correlation for all oils. This correlation is plotted alongside the corresponding values for water in Figure 1. At all temperatures, water is a much better conductor of heat than oil.

*Appendix: Temperature dependence of the physical properties of water***.** The ultrasonic velocity, specific heat, and thermal conductivity of water can be calculated from the general equation (6,7):

$$X = \sum_{i=0}^{n} k_i T^i \qquad [5]$$

where X is the parameter of interest, and k_i are constants listed in Table 4. The other parameters are defined by specific equations (7):

Viscosity, 0–20°C:

$$\log \eta = \frac{1301}{\sum_{i=0}^{3} k_i (T-20)^i} - 1.30233 \qquad [6]$$

Viscosity, >20–100°C:

$$\log \eta = \frac{k_1(20-T) + k_2(20-T)^2}{T+105} \log \eta_{20} \qquad [7]$$

where η_{20} is the viscosity at 20°C calculated from Equation 7 (= 1.002 mPa·s).

Density:

$$\rho = \frac{\sum_{i=0}^{5} k_i T^i}{1 + k_6 T} \qquad [8]$$

The thermal expansion coefficient can be calculated from constants used in Equation 8 by the same approach taken with the oil above. The relevant constants, k_i , for these equations are listed in Table 4.

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TABLE 4
Constants to Predict Thermophysical Properties of Water from Equations 5–8

	k_0	k_1	k_2	k_3	k_4	k_5	k_6
c (m·s^{-1})	1.40238754E + 03	5.03711129	−5.80852166E − 02	3.34198834E − 04	−1.47800417E − 06	3.14643091E − 09	
Cp (J·kg^{-1}·°C^{-1})	4.1762	−9.0864E − 05	5.4731E − 06	0	0	0	0
ρ (kg·m^{-3})	9.9983952E + 02	1.6945176E + 01	−7.9870401E − 03	−4.6170461E − 05	1.0556302E − 07	−2.8054253E − 10	1.6879850E − 02
τ (W·m^{-1}·°C^{-1})	5.7109E − 01	1.7625E − 03	−6.7036E − 06	0	0	0	0
η (mPa·s) ($T < 20$°C)	9.98333E + 02	8.1855	5.85E − 03	1.30233			
η (mPa·s) ($T > 20$°C)	1.3272	−1.053E − 03					

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