DENSITY AND ULTRASONIC STUDIES ON SUNFLOWER OIL

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Abstract

In the present communication, the results of ultrasonic and density studies were reported for the sunflower oil with the temperature variation. As we know that in present days sunflower oil is one of the most interested oils for cooking for good health. It contains Oleic acid and Linoleic acids in large portion. While cooking, definitely with the temperature variation there may be a change in that oil, because the available oils are genetically modified to produce the higher contents of mono unsaturates and poly unsaturates. The studies on intermolecular changes in the sunflower oil were carried with the ultrasonic and density measurements. The results of these studies reveal the change in ultrasonic velocity and density of Sunflower oil with temperature. Using these results we calculated few thermodynamic parameters like molar volume, adiabatic compressibility, molecular free length, acoustic impedance, Rao's constant and Wada's constant. By observing the changes of above parameters with temperature it is able to know the intermolecular interactions. The theoretical values of ultrasonic velocities and densities are compared with experimental values and are in good agreement. These studies will be useful for producing better and efficient sunflower oil for good health.

Index Terms: *Density, Ultrasonic Velocity, Sunflower Oil, Thermo Acoustic Parameters, Fatty Acids..*

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1. INTRODUCTION:

Sunflower oil has large amounts of Oleic acid and Linoleic acids and is said to be good for heart. So people are trying to produce sunflower oil with higher contents of mono unsaturates and poly unsaturates by genetically modifying the sunflower crops. These oils are heated while cooking. So it is important to know what changes are going inside the oil while heating. One method to know the internal changes in oil while heating is ultrasonic method. If we observe the density changes along with ultrasonic changes, we can calculate some of the thermodynamic parameters. The changes in the thermodynamic parameters with temperature will give us the knowledge of inter molecular interactions taking place in the oil while heating.

Previous workers like Gouw and Vultger [1], Javanaud and Radhalkar [2], McClements and Powey [3] calculated the ultrasonic velocities of oils from the knowledge of the fatty acid contents in the oils. Similarly some of the workers calculated the density theoretically using Lund's [4] equation and modified Rackett equation [5-6].

In our present study we studied the change in ultrasonic velocity and density of Sunflower oil with temperature. Using these values we calculated few thermodynamic parameters like molar volume, adiabatic compressibility, molecular free length, acoustic impedance, Rao's constant and Wada's constant. Observing the changes of above parameters with temperature we are able to know the intermolecular interactions. The theoretical values of ultrasonic velocities and densities are compared with experimental values. A few values of ultrasonic velocities are proposed for simple triglycerides with the help of Javanadu Radhalkar [2] equations, Gouw and Vultger [1] values and Mc Clements and Powey[3] values and equations. The theoretical values of ultrasonic velocities calculated from proposed values are compared with experimental values.

2. MATERIALS AND METHODS:

The Sunflower oil used was manufactured and packed by Agrotech foods, Secunderabad by Priyanka Refineries. Density of oil is measured using specific gravity bottle method from 30^0C to 60^0C. The weights of specific gravity bottle with oil are measured using electronic balance of Adair Dutt Instruments private. Its capacity is 50gm and readability is 0.001 gm. To heat the specific gravity bottle to different temperatures, a constant temperature bath made by MC Dalal agencies is used. Eurolab digital thermometer with temperature range -50^{0}C to 200^{0}C is used. It is accurate up to 0.1^{0}C.

Ultrasonic velocities of Sunflower oil is measured with ultrasonic interferometer (Mittal enterprises, New Delhi, Model F81) of accuracy +/_ 0.05% at 2MHz. Accuracy in velocity measurement is 0.1m/s. It is calibrated with water and benzene. The ultrasonic velocities and densities are determined from 30^{0}C to 60^{0}C.The temperature stability is maintained within +/-0.01K by circulating water around interferometer cell with a circulating pump of thermostatic water bath for thermal stability.

Using density and ultrasonic velocity values, the thermodynamic parameters such as adiabatic compressibility, Rao's constant, Wada's constant and mean free length values are calculated from 30^{0}C to 60^{0}C. The percentages of different fatty acids in the sunflower oil used in experiment are given below. This data is taken from the website of the manufacturing company. Molecular weight of Sunflower oil is calculated to be 869.6 from the Fatty acid data.

Table 1: percentage of different fatty acids in sunflower oil

Acid	Number	% of acid in oil Literature value	% of acid in oil Sundrop
Palmitic	16:0	5.6	6.6
Stearic	18:0	2.2	3.4
Oleic	18:1	25.1	25
Linoleic	18:2	66.2	65

3. RESULTS AND DISCUSSION:

The density, ultrasonic velocity and other thermodynamic parameters of Sunflower oil observed by the author are shown in Table 2.

Table 2: Typical parameters of Sunflower oil

Temp. in K	ρ kg/m^3	Um/s	V cu.m/mol	β*10^{-10} m^2/newton	L(f)* 10^{-15}m	Z*10^5 kg/m^2/s	R m^3/mol (ms^{-1})$^{1/3}$	W m^3/mol/(m^2/newton)$^{1/7}$
303	911.8	1440.8	0.954	5.283	1.096	13.137	10.7457	20.1707
308	909.1	1426.53	0.957	5.405	1.132	12.969	10.7420	20.1646
313	907.5	1409.9	0.958	5.543	1.171	12.795	10.7190	20.1275
318	905.7	1390.3	0.960	5.712	1.217	12.592	10.6903	20.0813
323	900.9	1378.4	0.965	5.842	1.256	12.418	10.7165	20.1235
328	896.4	1357.3	0.970	6.055	1.313	12.167	10.7152	20.1212
333	894.5	1346.08	0.972	6.170	1.350	12.041	10.7083	20.1101

3.1 Density:

Density values observed by author at different temperatures for Sunflower oil along with reference values are shown in Table3.

Table 3: Experimental Densities of Sunflower Oil

OIL	Densitykg/m^3 Present work	SV	density reported	SV	Temp(K)	Ref.
SF	911.8	193.6	921.6	191	303.15	[7]
	907.5		910.4		313.15	[7]
	900.9		902.1		323.15	[7]
	894.5		896.5		333.15	[7]
	907.5		906.2	189	313.15	[1]
	907.5		909.1	192	313.15	[1]
	907.5		906.0	195	313.15	[1]
	911.8	193.6	915.46		303.15	[8]
	909.1		912.41		308.15	[8]
	907.5		909.36		313.15	[8]
	905.7		906.31		318.15	[8]
	900.9		903.26		323.15	[8]
	896.4		900.21		328.15	[8]
	894.5		897.16		333.15	[8]

Density of Glycerol is 1.228 at room temperature and fatty acid with carbon number 18 is around 0.8742. So the density of oils which are mixed triglycerides is somewhere in between these two densities. Table 2 shows the comparison between the reference density values and density values in present work. They are in similar ranges for Sunflower oil.

Rackett developed an equation for liquid density over a wide range of temperature and it is modified by Spencer and Danner [6]. Modified Rackett equation for Molar volume is

$$V_s = \left(\frac{R_c T_c}{P_c}\right) Z_{RA}^{\left[1+(1-T_r)^{\frac{2}{7}}\right]} \quad (1)$$

V_C, T_c, and P_c are critical volume, temperature and pressure respectively. Z_{RA} is Racket parameter. T_r is the reduced temperature.

Density estimation for a liquid mixture as extension to modified Racket equation is given by Spencer and Danner [6].

$$V_{s,mix} = R\left[\frac{\sum x_i T_{ci}}{P_{ci}}\right]\left[\sum x_i Z_{RAi}\right]^{\left[1+(1-T_r)^{\frac{2}{7}}\right]} \quad (2)$$

$$\rho = \sum \frac{x_i MW_i}{V_{smix}} \quad (3)$$

A correction factor was plotted against the MW_{oil} of that oil for a number of oils. The correction factor for oils with MW>is

$$F_c=0.0236+0.000082(875-MW_{oil}) \quad (4)$$

And MW<875 is

$$F_c = 0.0236 + 0.000098(875 - MW_{oil}) \quad (5)$$

Thus the density of vegetable oil is given by

$$\rho_{oil} = \frac{\left(\sum x_i MW_i\right)}{R\left[\sum \frac{x_i T_{ci}}{P_{ci}}\right]\left(\sum x_i Z_{RAi}\right)^{\left[1+(1-T_r)^{7^{\frac{2}{}}}\right]}} + F_c \quad (6)$$

Using the critical parameters for fatty acids present in our oil and percentages of Fatty acids in the oil, the density of Sunflower oil is calculated and compared with experimental value in Table4.

Table 4: Density of Sunflower Oil at different Temperatures

T_i	ρ(theor)	ρ(exp)	Percentage of error
303	928.39	911.8	-1.82
308	925.02	909.1	-1.75
313	921.64	907.5	-1.56
318	918.25	905.7	-1.39
323	914.85	900.9	-1.55
328	911.43	896.4	-1.68
333	908.00	894.5	-1.51

Table 4 gives the comparison between the densities of sunflower oil determined experimentally and calculated theoretically from modified Rackett equation. Last column of the table gives percentage of error between two values. The percentage error is less than 2% in present case.

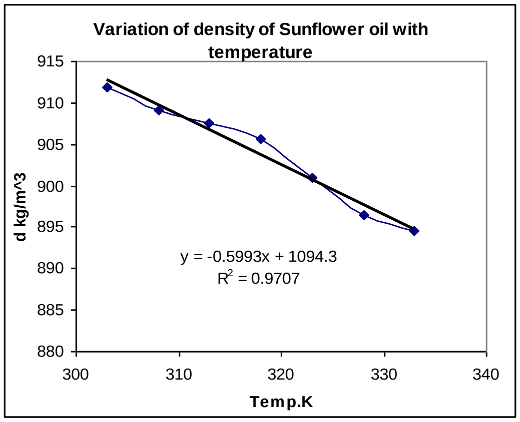


Fig-1: Variation of Density of Sunflower oil with temperature

The Fig-1 drawn for variation of density with temperature indicates that the density decreases with increase of temperature, but not perfectly linear. The nonlinear decrease in the present case is expected because the oil is not a single component liquid but is a mixture of triglycerides. This result is substantiated if we observe the thermal expansion coefficients listed in table 4. The expansion of oil on heating is more from 30^0C to 45^0C. Then expansion is reducing with increase of temperature. The decrease of density with temperature has a slope of -0.5993m/s.The change in density with temperature is fitting well into the polynomial form with R^2 coefficient of 0.9832. The density variation with temperature can be shown by the polynomial equation

$$\rho(t) = (-0.0079)t^2 + 4.3979t + 300.51$$

3.2 Thermal expansion coefficient α:

The thermal expansion coefficients α is given by

$$\alpha = \left[\frac{\rho_2 t_2 - \rho_1 t_1}{\rho_1 - \rho_2}\right] * \rho_1 \rho_2 \quad (7)$$

The thermal expansion coefficients of Sunflower oil at different temperatures are listed in second column of Table 5. The expansion coefficients at different temperatures with respect to room temperature 303K are given in third column.

Table 5: Thermal Expansion Coefficient at different temperatures of sunflower oil

Temp.K	$\alpha*10^4$	$\alpha'*10^4$
308	0.1371	0.1371
313	0.2311	0.1721
318	0.2035	0.1814
323	0.0729	0.1333
328	0.0764	0.1165

333	0.1843	0.1241

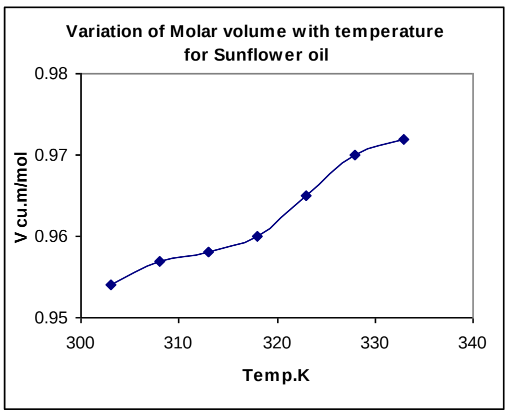
The average expansion coefficient of Sunflower oil is $0.1509*10^4$. The expansion coefficient is maximum between 308.15K and 318.15K. The expansion is decreasing with increase of temperature. Again the expansion is increasing from 333.15K. May be some of the semi crystallinity in a triglyceride due to saturated fatty acid component in oil is lost at 318.15 K causing larger expansion of liquid. At 333.15K the distance between oil molecules is increasing with temperature.

3.3 Temperature variation of observed molar volume of sunflower oil

Moalr volume is given by $$V = \frac{M.Wt}{\rho}$$ (8)

Where M.Wt is the molecular weight of the oil and ρ is the density of the oil.

Fig- 2: Temperature Vs Molar Volume



Variation of Molar volume of Sunflower oil with temperature is shown in the Fig-2. Molar volume increased with temperature indicating that the intermolecular space increased with temperature. After 313K rise in molar volume is steep than in the earlier portion of the Fig-. This indicates that at higher temperatures there is loosening of packing in triglyceride molecules that naturally leads to more intermolecular spacing.

3.4 Ultrasonic velocity:

The ultrasonic velocity determined experimentally is compared with ultrasonic velocities determined in different references are shown in the Table 6.

Table 6: Experimental Ultrasonic Velocity

OIL	Ultrasonic Velocity m/s Present work	SV	Ultrasonic velocity m/s reported	SV	Temp K	Ref.
SF	1440.8	193.6	1443.1	191	303.15	[7]
	1409.9	193.6	1406	189	313.15	[1]
			1408	192	313.15	[1]
			1403	195	313.15	[1]
	1440.8	193.6	1446	189.23	303.15	[9]
	1426.5	193.6	1437	189.23	308.15	[9]
	1409.9	193.6	1422	189.23	313.15	[9]
	1390.3	193.6	1407	189.23	318.15	[9]
	1378.4	193.6	1390	189.23	323.15	[9]
	1357.3	193.6	1374	189.23	328.15	[9]
	1346.1	193.6	1353	189.23	333.15	[9]

From Table 6 we can say lower the Saponification value of the sunflower oil, higher is its ultrasonic velocity at different temperatures. Such relation ship is not found in case of densities.

Comparison of experimental ultrasonic velocities with theoretically calculated velocities:

Javanadu and Radhalkar [2] have taken the formula of Hustad etal and generalized it to calculate the velocity of sound in oils. The generalized equation for multicomponent mixtures is given as

is $$u = \sum_{i=1}^{p} \beta_i u_i \quad (9)$$

Where u_i is the velocity of ith component of triglyceride of volume fraction or weight fraction β_i and

$$\sum_{i=1}^{p} \beta_i = 1 \quad (10)$$

Using above equation and considering the oil as mixed triglyceride, the ultrasonic velocity of the oil is calculated using the ultrasonic velocities of different single triglycerides given by Mc Clements and Powey [3] at 70^0C. The experimental values of oil measured from 30^0C to 60^0C are extrapolated to 70^0C and compared with theoretically calculated ultrasonic velocities. The error % is calculated and listed in Table 7.

The Wood equation given in Mc Clements and Powey [3]

$$u = \left[\left(\sum_{i=1}^{n} \frac{\phi_i}{u_i^2 \rho_i}\right)\left(\sum_{i=1}^{n} \phi_i \rho_i\right)\right]^{\frac{-1}{2}} \qquad (11)$$

Where u is the velocity, ρ is the density and Φ is the volume fraction or mass fraction, n is the number of components. For many oils the densities of different component is almost same so the velocity of mixed triglyceride can be simplified to the following form.

$$u = \left[\sum_{i=1}^{n} \frac{\phi_i}{u_i^2}\right]^{\frac{-1}{2}} \qquad (12)$$

Using above equation and considering oil as mixture of fatty acids in triglyceride form, the ultrasonic velocity of sunflower oil at 70^0C is calculated and compared with experimental value (extrapolated) shown in Table 7 5 and 6 th columns.The percentage errors are less than 1%. But with these formulas and data we are able to find the ultrasonic velocity only at 70^0C. So we proposed some velocity values for simple triglycerides at different temperatures and used them to calculate the ultrasonic velocities of oils at different temperatures theoretically.

Table 7: Comparison of Ultrasonic Velocities

Temp	U(Theory)	U(exp)	Percentage of error	U(Theory)	% Error
343 K	1305.8	1311.64	0.44	1323.6	-0.91

Using Javanadu and Radhalkar [2] equation to calculate ultrasonic velocity for triglyceride molecule from a given fatty acid is given by

$U=u_o+u_1n+u_2m$ (13)

Where n is number of carbon atoms in the component fatty acid, m number of carbon double bonds, u_o, u_1, u_2 are constants. Mc Clements and Powey [3] modified above equation for second double bond present in poly saturates. They suggested the equation

$$u = u_o + nu_1 + mu_2 + ou_3 \qquad (14)$$

Where u_o=1187.1+/-3m/s, u_1=2.12+/-0.07m/s , u_2=0.7=/-0.4m/s and u_3=3.5 m/s. u_2 is the increase in velocity due to the addition of an unsaturated bond to saturated fatty acid chain, u_3 is the increase in velocity due to addition of unsaturated bond to unsaturated fatty acid chain. n is the total no. of carbons in fatty acid chain, m is the number of unsaturated fatty acid chains per triglyceride molecule, o is the total no. of unsaturated bonds in triglyceride excluding the first on each unsaturated fatty acid chain. The u values of different simple triglycerides given by Mc Clements and Powey [3] at 70^0C and at 40^0C by Gouw and Vultger [1]. Using the knowledge of ultrasonic velocities of simple triglycerides, we tried to propose the ultrasonic velocities of each simple triglyceride in temperature range 30^0C to 60^0C. These values are used and considering the oil as a mixture of simple triglycerides, the ultrasonic velocity is calculated from the proportions of simple triglycerides present in the oil. The ultrasonic velocity is calculated using the formula

$$u = \sum_{i=1}^{p} \beta_i u_i \qquad (15)$$

Above equation is similar to the generalized equation of Hustad etal given in paper of Javanadu and Radhalkar [2]. These theoretical values are compared with experimental values and % of error is also listed in Table 5.2.1i. The proposed u values for simple triglycerides at different temperatures are listed in Table8.

Table 8: Ultrasonic Velocities for different Triglycerides

Triglyceride	PPP	SSS	OOO	LLL	LnLnLn
Temp	U m/s	U m/s	U m/s	U m/s	U m/s
303K	1431.2	1444.4	1447.7	1447.7	1444.7
308K	1414.2	1427.4	1430.7	1430.7	1430.7
313K	1397.2	1410.4	1413.7	1413.7	1413.7
318K	1380.2	1393.4	1396.7	1396.7	1399.7
323K	1363.2	1376.4	1379.7	1379.7	1385.7
328K	1346.2	1359.4	1362.7	1362.7	1374.7
333K	1329.2	1342.4	1345.7	1345.7	1360.7

PPP-Simple Palmitic Triglyceride, SSS- Simple Stearic Triglyceride, OOO-Simple Oleic Triglyceride, LLL-Simple Linoleic Triglyceride, LnLnLn- Simple Linolenic Triglyceride.

Table 9: Comparison of Ultrasonic Velocities

Temperature	U m/s(Theor)	U m/s (exp)	Percentage error

303K	1440.63	1440.8	0.01
308K	1423.78	1426.53	0.19
313K	1406.93	1409.9	0.21
318K	1390.08	1390.3	0.02
323K	1373.24	1378.4	0.37
328K	1356.39	1357.3	0.07
333K	1339.54	1346.08	0.49

From the table 9 we may observe that percentage error is maximum 0.49% using proposed values for simple triglycerides. The % error values are as low as 0.01% at certain temperatures. The % errors in case of wood equation simplified by Mc Clements and Powey [3], and Hustad equation simplified by Javanadu and Radhalkar [2] are also less than 1%. So we can calculate the ultrasonic velocities at different temperatures for oils from the knowledge of fatty acids proportions in the oil.

3.5 Temperature variation of observed ultrasonic velocity of sunflower oil:

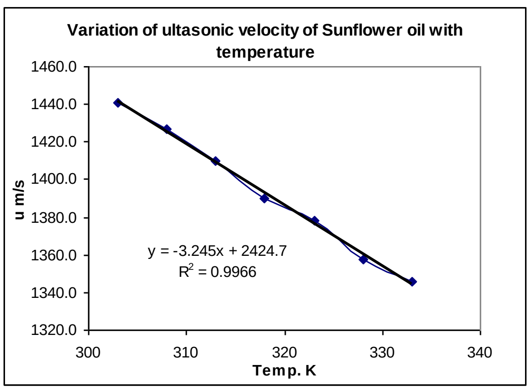


Fig-3: Temperature Vs Ultrasonic Velocity

The Fig. of the temperature dependence of ultrasonic velocity shows a linear decrease with temperature. Decrease in ultrasonic velocity results when intermolecular space increases due to weakening of intermolecular attraction.

The linear fit value of change in velocity with temperature gives a slope of -3.2437m/s and u(o) value equal to 1538.7m/s in present study(temperature in ^{0}C). Mc Clements and Powey[3] have given a slope of -3.28m/s and u(o)=1538m/s. Coupland and Julian Mc clements[8] have given a value of slope as -3.3m/s and u(o)=1537.6m/s. The slower decrease of u value with temperature compared to reference value may be due to Sunflower we used is more refined.

With the knowledge of density, molecular weight, ultrasonic velocity, a number of thermodynamic parameters can be evaluated. Details of results regarding some thermodynamic parameters are given below.

Temperature variation of adiabatic compressibility β_s or β_{ad} of Sunflower oil: Adiabatic compressibility can be calculated from density and ultrasonic velocity values using the below formula in Eq.(16) [10-13].

$$\beta_{ad} = \frac{1}{\rho u^2} \quad (16)$$

Variation of adiabatic compressibility with temperature in pure sunflower oil is almost linear and it increased with increase of temperature.

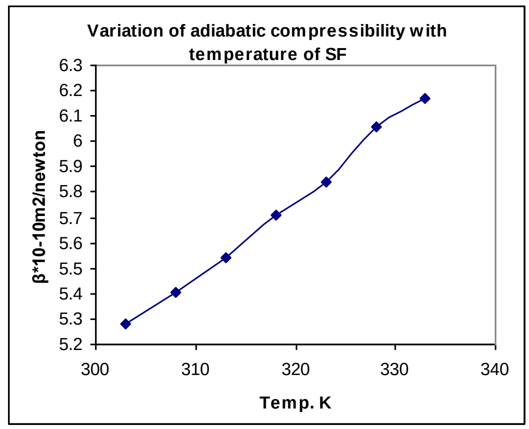


Fig-4: Temperature Vs Adiabatic Compressibility

From the data , as the ultrasonic velocity decreases the adiabatic compressibility increases with temperature as expected. The ease with which the medium can be compressed is given by the compressibility values. The higher compressibility value indicates that the medium is loosely packed.

3.6 Temperature variation of observed available volume of sunflower oil :

The available volume is the difference between the actual volume and the minimum possible volume i.e

The available volume = molar volume at temperature T - the molar volume at absolute zero

$$V_a = V_T - V_o \quad (17)$$

Or

$$V_a = V * \left[1 - \frac{u}{u_\infty}\right]$$

Its values are listed in table 10.

Table 10: Dependence of Available Volume on temperature

Temp.K	V_a Cu.m
303	0.0949
308	0.1037
313	0.1139
318	0.1258
323	0.1337
328	0.1472
333	0.1592

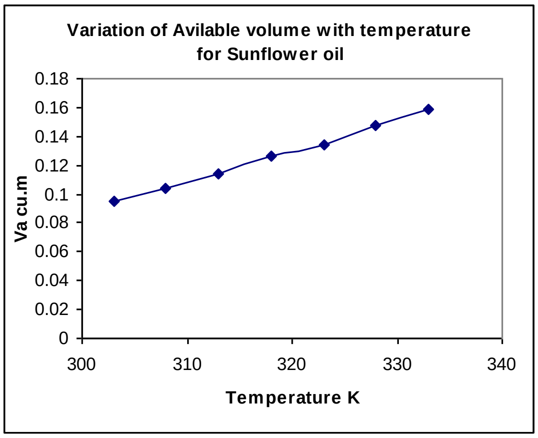


Fig--5: Temperature Vs Volume$_{\text{available}}$

From Fig--5, Variation of available volume with temperature in pure sunflower oil is almost linear and it increased with increase of temperature.

Temperature variation of acoustic impedance of sunflower oil: Acoustic impedance is given by

$$Z = u \times \rho \text{ kg m}^{-2} \text{ s}^{-1} \quad (18)$$

The temperature variation of acoustic impedance is given in Fig--6. It is linearly decreasing with temperature. So the expansion of liquid due to heating is creating large spaces between the triglyceride molecules causing impedance to ultrasonic waves passing through the liquid.

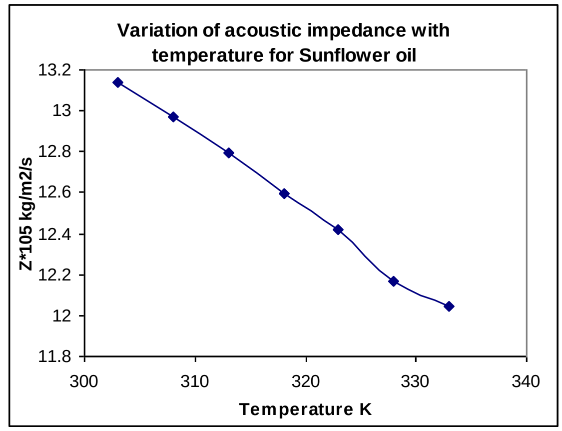


Fig-6: Temperature Vs Acoustic Impedance

3.7 Rao' s constant or Molar sound Velocity:

Rao observed that the product $Vu^{1/3}$ is a constant for liquids. At almost the same time Schaaffs also proposed his law that for sufficiently high pressures the product of molar volume (V) and cube root of sound velocity (u) is constant.

$$Vu^{1/3} = R = (M/\rho)\, u^{1/3} \quad (19)$$

$(M/\rho)\, u^{1/3}$ is called Molar sound velocity. Subsequent workers symbolized it as 'R' and it is being called now as Rao's constant.

Rao's Constant R is given by

$$R = \frac{M}{\rho} * u^{\frac{1}{3}} \quad (20)$$

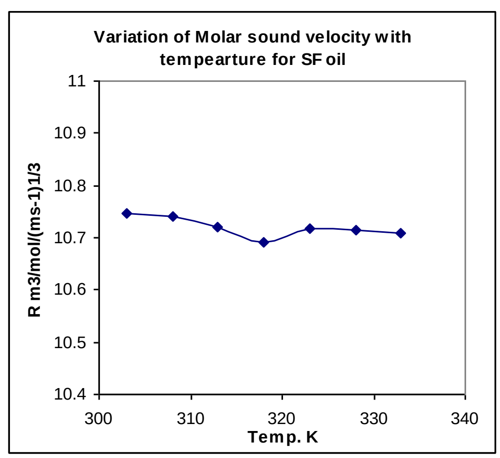


Fig--7: Temperature Vs Molar Sound Velocity

Fig--7 gives the variation of R with temperature for Sunflower oil. Rao's constant is independent of temperature from Fig-, for Sunflower oil. So we may say that the triglyceride molecules in the Sunflower oil are not associated with temperature variations also.

3.8 The intermolecular free length:

The intermolecular free length is the distance covered by a sound wave between the surfaces of two molecules.

$$uL_f \rho^{\frac{1}{2}} = k(const.) \qquad (21)$$

$$\frac{L_f}{\beta_{ad}} = k \Rightarrow L_f = k * \beta_{ad} \qquad (22)$$

From Fig-8 we may say that there is linear increase in molecular free length with temperature

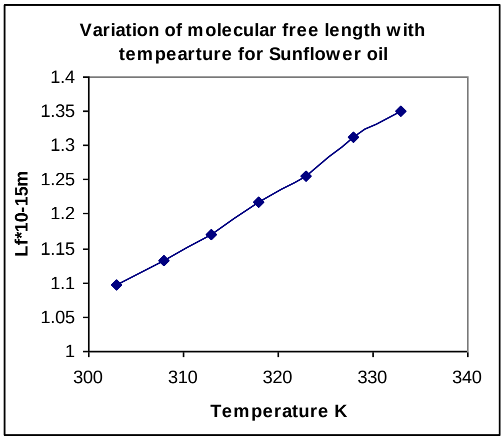


Fig--8: Temperature Vs Molecular Free Length

Variation of Surface tension of Sunflower oil with temperature:

Surface tension is related to ultrasonic velocity and density by the relation

$$u = \left(\frac{\sigma}{6.3 * 10^{-4} \rho} \right)^{\frac{2}{3}}$$

From Table 11 we can say Surface tension decreased with temperature rise.

Table11: Temperature Vs Surface tension

Temp in K	surface tension*10^3
303.15	31.416
308.15	30.858
313.15	30.267
318.15	29.579
323.15	29.046
328.15	28.239
333.15	27.747

3.9 Wada's constant or Moalr compressibility W:

Wada observed that $\rho\beta_{ad}^{1/7}$ is independent of both temperature and pressure of any liquid. He defined $W=(M/\rho)\beta_{ad}^{-1/7}$ as Molecular adiabatic compressibility. It is now popularly known as Wada's constant.

Wada's constant is given by

$$W = \frac{M}{\rho} * \frac{1}{\beta^{\frac{1}{7}}} \qquad (23)$$

Table 12: Temperature Vs Wada's Constant

Temp in K	W $m^3/mol/(m^2/newton)^{1/7}$
303.15	20.1707
308.15	20.1646
313.15	20.1275
318.15	20.0813
323.15	20.1235
328.15	20. 1212
333.15	20.1101

From Table 12 we can say that Wada's constant is almost constant with temperature

4. CONCLUSIONS:

The variation of density with temperature for refined sunflower oil is not perfectly linear. The densities of sunflower oil calculated from modified Rackett equation theoretically are showing only 2% error. So it can be used to calculate densities theoretically. The thermal expansion of oil is more between the temperatures 30^0C to 45^0C. Molar volume changes with temperature indicate that there is loose packing of molecules at higher temperatures (above 50C). Variation between theoretically calculated velocities and experimental ultrasonic velocities is maximum 0.5% only by the values proposed by Mc Cllements etal, Javanaud etal and by the author. So these methods can be used to calculate the ultrasonic velocities of oils theoretically.The molecular free length and adiabatic compressibility are increasing with temperature. This may be due to breakages of weak polar bonds between the polar ends of triglyceride molecules. The rao's constant is almost same at all temperatures. This implies there is no strong association between oil molecules.

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