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Ultrasonic Study of Power Transformer Oil at Different Temperatures

Manoj Kumar Praharaj[1] and Sarmistha Mishra[2]
[1]Associate Professor, Department of Physics, Ajay Binay Institute of Technology, Cuttack, Odisha, India.
[2]Rtd. Professor, Department of Physics, Ravenshaw (Autonomous) College, Cuttack, Odisha, India.
Corresponding Author Email: m_praharaj@rediffmail.com .

Abstract: *Using an ultrasonic interferometer, unused pure transformer oil was compared to used oil that had been utilized for one and two years. The fluid density affects ultrasonic readings. We can investigate the ultrasonic velocity and, consequently, the various thermo-acoustic characteristics, such as adiabatic compressibility, acoustic impedance, relaxation time, Rao's constant, Wada's constant, etc., by measuring the fluid density at various temperatures. This paper has examined in depth how the parameters change with temperature. For all the three types of transformer oil.*

Keywords: Transformer oil, density, thermo-acoustic parameters, and ultrasonic velocity

I. INTRODUCTION

An essential component of any functioning transformer is transformer oil [1–8]. Two crucial tasks are carried out by transformer oil. When combined with the insulating materials found in the conductors and coils, it produces an adequate degree of insulation. In order to remove heat from the windings and core, it also serves as a coolant [9–11]. The paraffin-based natural mineral oil used in India has a lengthy hydrocarbon chain with the usual chemical formula C_nH_{2n+2} [12]. When the transformer is operating, the oil serves as both an insulator and a heat exchanger. The oil experiences physical and chemical changes because of the mechanical and electrical stresses it experiences during transformer operation [13–15]. Another important factor is the transformer oil's age. Oxidation is the primary cause of the hydrocarbon base of oil's breakdown. Peroxides, alcohols, ketones, and acids are produced in this situation. Additionally, moisture can lower the insulating oil's breakdown voltage. Additionally, chemical reactions with windings and other solid insulations might contaminate the area. The insulating properties of oilpaper insulation are also disrupted by the presence of caustic Sulphur.

II. MATERIALS AND METHOD

Three transformer oil samples were examined, for this study and were given the following labels:
TO1: Transformer oil that was created in 2023 and is fresh (unused).
TO2: One year's worth of transformer oil produced in 2021
TO3: Transformer oil that has been used for two years and was produced in 2019.
Every sample has an Indian IS-335: 1993 label.
At various temperatures, the density, viscosity, and ultrasonic velocity were measured. An ultrasonic interferometer (Model M-84, provided by M/S Mittal Enterprises, New Delhi) was used to detect ultrasonic velocity at 4 MHz with an accuracy of ±0.1 $m \cdot s^{-1}$. An interferometer's measuring cell is a specially made, double-walled vessel with temperature stability built in. Water has been circulated through the outer jacket of the double-walled measuring cell containing the transformer oil using an electronically operated digital constant temperature bath (Model SSI-03 Spl, supplied by M/S Mittal Enterprises, New Delhi) that operates in the temperature range of −10°C to 85°C with an accuracy of ±0.1°C. The LOVIS-2000 M/ME of Anton Parr, which is suitable for low viscosity liquids at various temperatures and operates on the rolling ball principle, was used to measure the viscosity of each sample. The Anton-Parr DSA5000M Density

meter with an oscillating U-tube was used to measure the density of each sample. The U-tube's temperature was controlled by an integrated Peltier thermostat.

III. THEORY

Using the density, viscosity, and ultrasonic velocity measurements, the following thermodynamic parameters were computed.

(i) Adiabatic Compressibility (β): Using Newton Laplace's equation [18} we can compute by using the relation

$$\beta = 1/U^2.\rho$$

(ii) Intermolecular free length (L_f): The relation [19] used to compute is

$$L_f = K_T\beta^{1/2}$$

The temperature-dependent constant known as Jacobson's constant, is K_T={(93.875+0.375T) x10^{-8}} [20].

(iii) Free volume (V_f): free volume [21,22] can be computed by using the formula.

$$V_f = (M_{eff}.U/K.\eta)^{3/2}.$$

Where, K = 4.281 x 10^9 [23] is a dimensionless constant that is independent of temperature and liquid, and "Meff" is the effective molecular weight is its value.

(iv) Internal Pressure (πi): The relation used to compute is [24].

$$\pi_i = BRT\ (K\eta/U)^{1/2}\ (\rho^{2/3}/M^{7/6})$$

Where R is the universal gas constant, "b" is cubic packing, which is taken to be "2" for all liquids.

(v) Relaxation time (τ): The relationship used to calculate the relaxation time.

$$\tau = 4/3.\ (\beta.\eta)$$

(vi) Acoustic impedance (Z):. Acoustic impedance [25–26], can be calculated by using the relation

$$Z = U.\rho$$

(vii) Gibb's free energy (ΔG): The relation used to determine the Gibb's free energy. is

$$\Delta G = kT.\ln\ (kT\tau/h).$$

Where, "h" stands for Planck's constant and "k" for Boltzmann's constant.

(viii) Available Volume: Schaff et al. [21, 27] demonstrated the relation, used to determine the available volume.

$$Va = Vm(1-U/U\infty)$$

For a liquid mixture, U∞= the Schaaf's limiting value, which is 1600 m/s.

U = mixture's ultrasonic velocity

(ix) Rao's constant (R): It can be calculated using an equation provided by Bagchi et al.

$$R = \left(\frac{M_{eff}}{\rho}\right).U^{\frac{1}{3}} = V_m.U^{\frac{1}{3}}$$

(x) Wada's constant: It is determined by using the relation

$$W = \left(\frac{M_{eff}}{\rho}\right).\beta^{\frac{-1}{7}}$$

(xi) Surface tension: The relation can be used to compute surface tension.

$$S = 6.3\ X\ 10^{-4}.\rho.U^{\frac{3}{2}}$$

IV. RESULT AND DISCUSSION

Experimental value of ultrasonic velocity, density and viscosity are presented in Table-1. Calculated values of acoustical parameters are presented in Table-2 and 3. Variation of some parametrs with temperatures are shown in fig-1 to fig.-4.

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TABLE-1

Power Transformer Oil	Density (ρ) (kg/m^3)				Viscosity(η) NSm^{-2} (x 10^{-3})				Velocity(V) ms^{-1}			
	303	313	323	333	303	313	323	333	303	313	323	333
TO-1(PURE)	828.76	822.73	817.53	814.03	15.510	12.466	10.999	9.521	1378.0	1353.0	1330.0	1305.0
TO-2 (1Y. USED)	831.43	825.12	819.78	815.77	14.677	11.814	10.408	8.837	1355.0	1338.4	1314.7	1284.1
TO-3 (2Y. USED)	833.67	828.03	821.62	818.37	14.293	11.513	9.789	8.356	1361.6	1345.2	1320.4	1296.4
TNO (NANO)	879.00	876.20	874.10	871.50	14.512	11.852	9.547	8.254	1379.7	1348.0	1318.3	1285.0

TABLE-2

Power Trans. Oil	Adiabatic Comp.				Relaxation time				Free Length			
	303	313	323	333	303	313	323	333	303	313	323	333
TO-1(PURE)	6.354	6.640	6.915	7.2134	13.141	11.036	10.141	9.157	0.4942	0.5103	0.5315	0.5455
TO-2 (1Y. USED)	6.551	6.766	7.058	7.4339	12.819	10.657	9.794	8.759	0.5017	0.5151	0.5370	0.5538
TO-3 (2Y. USED)	6.470	6.674	6.981	7.2706	12.330	10.245	9.111	8.100	0.4986	0.5116	0.5340	0.5476
TNO (NANO)	5.976	6.281	6.583	6.9491	11.564	9.925	8.379	7.647	0.4792	0.4963	0.5186	0.5354

TABLE-3

Power Transformer Oil	Acoustic impedance				Gibbs free energy				Internal Pressure x 10^6			
	303	313	323	333	303	313	323	333	303	313	323	333
TO-1 (PURE)	1.142	1.113	1.087	1.062	1.126	1.144	1.186	1.221	515.82	487.30	481.31	471.00
TO-2 (1Y. USED)	1.127	1.104	1.078	1.048	1.119	1.134	1.175	1.206	507.10	477.89	471.78	458.09
TO-3 (2Y. USED)	1.135	1.114	1.085	1.061	1.108	1.122	1.153	1.181	500.10	471.68	457.23	444.27
TNO (NANO)	1.213	1.181	1.152	1.120	1.090	1.113	1.127	1.163	518.59	496.44	470.95	462.50

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TABLE-4

Power Transformer Oil	Free Volume				Available volume				Molar Volume			
	303	313	323	333	303	313	323	333	303	313	323	333
TO-1(PURE)	0.066	0.090	0.105	0.127	0.029	0.032	0.035	0.039	0.205	0.207	0.208	0.209
TO-2 (1Y. USED)	0.070	0.096	0.113	0.139	0.031	0.034	0.037	0.041	0.205	0.206	0.208	0.209
TO-3 (2Y. USED)	0.074	0.100	0.124	0.153	0.030	0.033	0.036	0.039	0.204	0.206	0.207	0.208
TNO (NANO)	0.074	0.096	0.129	0.154	0.027	0.031	0.034	0.038	0.194	0.194	0.195	0.195

TABLE-5

Power Transformer Oil	Rao's Constant				Wada Constant,				Van der Waals' constant			
	303	313	323	333	303	313	323	333	303	313	323	333
TO-1(PURE)	2.286	2.289	2.290	2.286	0.1577	0.1579	0.1580	0.1577	0.1884	0.1869	0.1863	0.1852
TO-2 (1Y. USED)	2.266	2.274	2.275	2.268	0.1565	0.1570	0.1571	0.1567	0.1871	0.1857	0.1852	0.1840
TO-3 (2Y. USED)	2.263	2.270	2.273	2.268	0.1564	0.1568	0.1570	0.1567	0.1863	0.1848	0.1841	0.1828
TNO (NANO)	2.156	2.146	2.136	2.124	0.1500	0.1494	0.1488	0.1481	0.1769	0.1749	0.1727	0.1715

Since ultrasonic measurements are functions of density and as density is an important parameter, it was first measured as a function of temperature. Density decreases with increase in temperature for pure as well as used transformer oils. As temperature increases, the kinetic energy of the oil molecules increases, hence they get further apart resulting in increase of the volume of the sample. This cause a decrease in density as well as viscosity.

During the operation of the transformer oil, it is subjected to mechanical and electrical stress as. This may decrease the compactness of the used oil molecules as compared to pure oil. Hence, velocity decreases for used oil at all temperatures as compared to pure oil.

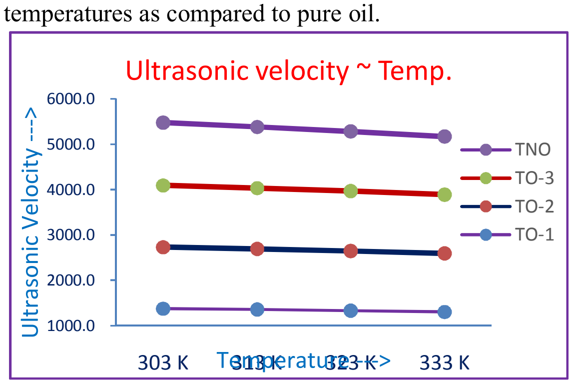

Fig-1: Variation of ultrasonic velocity with temp.

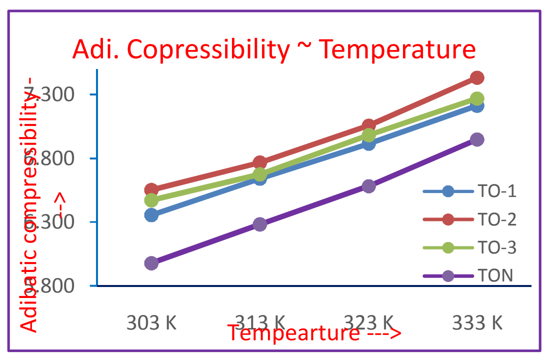

Fig-2: Variation of adiabatic comp. with temp.

Further, the velocity increases in 2 years used oil (TO3) of as compared to that of 1 year (TO2), although in both the cases, it is less than that of pure oil. When operated for a long period, there may be contamination caused by chemical interactions with winding and other solid insulations catalyzed by high operating temperature. The property of

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transformer oil changes which brings in the compactness of the molecular structure. This explain the increase in ultrasonic velocity in used transformer oil of 2 years as compared to 1 year used transformer oil (TO2).

The adiabatic compressibility is an essential factor in determining the degree of compactness of a medium. The effect of temperature on density and adiabatic compressibility are contradictory to each other. As intermolecular distance increases with increase in temperature, density decreases and compressibility increases. Free length and compressibility show similar behavior.

Acoustic relaxation time is the time taken for the excitation energy to appear as translational energy. When the ultrasonic wave passes through a medium, the molecules move out of their equilibrium position and take some time to return to it. The decrease in energy is caused by absorption and scattering. The absorption of sound wave result in the time lag between the passing of the ultrasonic wave and the return of the molecules to their equilibrium position. This time lag is the relaxation time, which depends on temperature and impurities. Relaxation time decreases rapidly as temperature increases for pure as well as used oils, where as it decreases with aging of oil at each temperature. Former indicates instantaneous conversion of excitation energy in to translational energy as the molecular motion increases rapidly as temperature increases. In the latter case temperature remains constant, but the structural property of the oil changes. Hence, the change in relaxation time is slower.

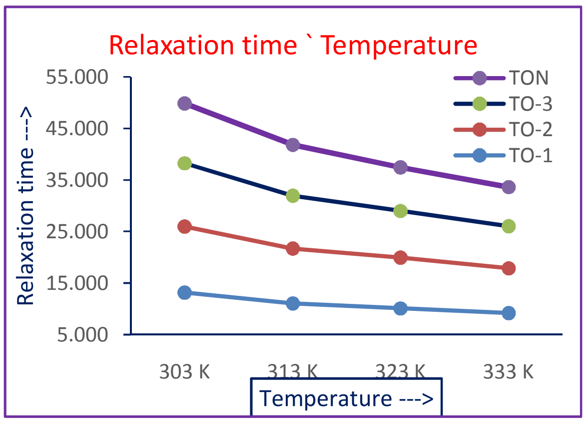

Fig-3: Variation of relaxation time with temperature.

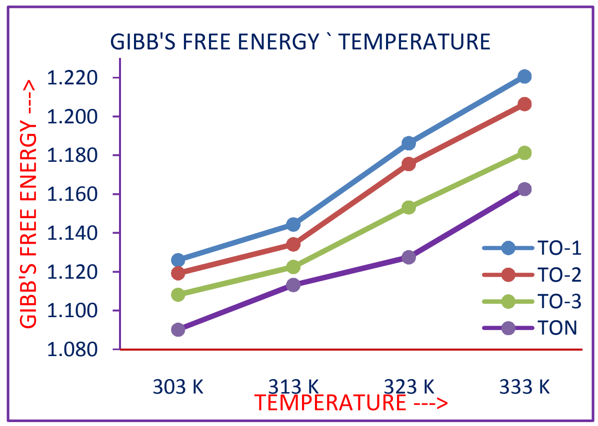

Fig-4: Variation of Gibbs' free energy with temperature.

Acoustic impedance of a medium is a fundamental concept to understand the generation and propagation of ultrasonic waves. Acoustic impedance represent the resistance to sound propagation through the medium. For pure as well as used oil, it slowly increases as temperature increases, which is obvious since velocity also decreases. The impedance slowly decreases as longevity of the oil increases. In this case, we have seen that the velocity increases.

Gibbs free energy is the available energy of a substance that can be used in a chemical reaction. Gibbs free energy decreases rapidly as temperature increases. As temperature increases, kinetic energy of molecule increases resulting in more collisions between them suggesting longer time taken for the rearrangement of the molecules in the oil. It is known that, in a spontaneous change, Gibbs energy always decreases.

$$\Delta G = \Delta H - T\Delta S$$

Where, ΔH is change in total energy and ΔS is change in entropy.

Internal pressure is a measure of totality of forces of dispersion, attraction and repulsion etc., that contribute to the overall cohesion of a liquid system. To compute the internal pressure, we need to measure the density, viscosity and ultrasonic velocity.

Expression for internal pressure using the free volume idea is

$$\pi_i = bRT(k\eta/u).(\rho^{2/3}/M^{7/6})$$

Where b, k, R, are constants, T is absolute temperature, u is the ultrasonic velocity, η is the viscosity and ρ is the density of liquid.

This indicates, when ultrasonic velocity decreases, internal pressure increases. Free volume is defined as the average volume in which the center of the molecules can move due to the repulsion of surrounding molecules.

Both Rao's constant and Wada's constant increase slowly with increase in temperature but decreases at higher temperature. In the latter case, weak molecular interaction is indicated. The decrease in the above constants also suggests the availability of less number of molecules in a given region and hence weak molecular interaction. In the former case, their inverse dependence on density indicates slight increase in Rao and Wada's constant with increase in temperature [28]. As density decreases, temperature increases. Wada's and Rao's constants are mathematically represented by

$$W = \beta^{1/7}.(M/\rho)\ ;\ \text{and} \quad R = U^{1/3}.(M/\rho)$$

Available volume and Molar volume are direct measure of the compactness and strength of binding between the molecules of any liquid. One can write the expression of the available volume as

$$V_a = (V - V_o)$$

Where V is molar volume at a given temperature and $V_o = M/\rho$ is the molar volume at absolute zero.

If the temperature is raised, the liquid expands as a whole through molecular collision although the molecules themselves do not expand. Hence molar volume increases as temperature increases [29].

Schaff's formula for available volume is given by

$$V_a = V(1 - U/U_\infty)$$

Where V is molar volume, U is ultrasonic velocity and $U_\infty = 1600$ m/s.

As ultrasonic velocity decreases, when temperature increases, according to Schaff's formula, available volume increases.

Vander Waal's constant provides the correction factor to the total volume occupied by the liquid [30]. The volume correction term adjusts the available volume by subtracting the volume occupied by the liquid molecules. The volume occupied by liquid molecule is negligible in comparison to the total volume of the liquids. As temperature increases, total volume expands hence the correction factor 'b' decreases in comparison to total volume.

Surface tension of liquid depends upon temperature, pressure, viscosity [31] etc. It is observed that surface tension decreases with increases in temperature for pure as well as used oils. When temperature increases, intermolecular forces decreases resulting in decrease in viscosity. This is the cause for decrease in surface tension as well.

During operation of the transformer, the oil is subjected to mechanical and electrical stress, which may decrease the compactness of the oil molecules in comparison to that of the pure oil. This is the reason for the decrease in velocity and the decrease in surface tension for oil of 1 year used in comparison to that of pure oil.

When the transformer is operated for a longer period, there may be contamination caused by chemical interaction of the oil with the winding and other solid insulation. Presence of impurities in the oil increases the surface tension. Hence, we observe that the surface tension of oil of 2 years is greater than that of 1 years.

V. CONCLUSION

In the current paper, authors have studied in detail the variation of the thermo-acoustic parameters with temperature, indicating the change in the intermolecular interactions that occurs in the oil, as it grows old and degrades.

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