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Non-Destructive Ultrasonic Evaluation of Transformer Oil Properties

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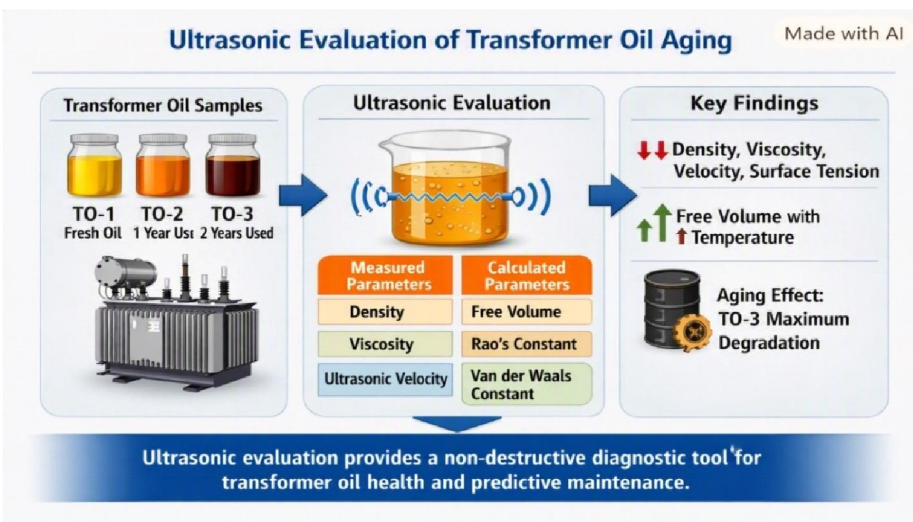
Abstract: *Transformer oils are critical for the reliable operation of power equipment, serving as both insulating and cooling media. Their properties degrade over time due to thermal stress, oxidation, and contamination, necessitating effective diagnostic techniques. Conventional methods such as dissolved gas analysis and chemical assays, while informative, are invasive and time consuming. In this study, a nondestructive ultrasonic approach was employed to evaluate the thermo-physical and acoustic properties of transformer oils at different temperatures and service ages. Experimental measurements of density, viscosity, and ultrasonic velocity were complemented by calculated parameters including free volume, molar volume, Rao's constant, Wada constant, Van der Waals constant, and surface tension.*
Results revealed systematic thermal trends: density, viscosity, ultrasonic velocity, and surface tension decreased with increasing temperature, while free volume and available volume increased. Aging effects were evident, with TO3 (two year used oil) exhibiting higher density, larger free volume, lower viscosity, and reduced acoustic constants compared to fresh oil (TO1). The correlation between free volume expansion and the decline in ultrasonic velocity and surface tension provides a quantitative measure of oil degradation. These findings confirm that ultrasonic evaluation offers a rapid, nondestructive, and reliable diagnostic tool for monitoring transformer oil health. The proposed methodology establishes a scientific basis for predictive maintenance strategies, enabling early detection of molecular degradation and extending transformer service life.

Graphical Abstract



Keywords: Transformer oil, Ultrasonic velocity, Temperature dependence, Dielectric properties, Non-destructive testing.

I. INTRODUCTION

Transformer oil plays a critical role in power systems, serving both as an insulating medium and a cooling agent for high voltage equipment. The reliability and longevity of transformers are strongly dependent on the physicochemical stability of the oil, which is continuously exposed to electrical stress, thermal fluctuations, and oxidative degradation during service. Conventional diagnostic methods—such as dissolved gas analysis (DGA), chemical assays, and dielectric spectroscopy—provide valuable insights but are often invasive, time consuming, and require specialized laboratory facilities **[1-10]**.These limitations highlight the need for rapid, nondestructive techniques that can monitor oil quality in real time.

Ultrasonic evaluation has emerged as a promising diagnostic tool for insulating liquids. The propagation of ultrasonic waves through transformer oil is highly sensitive to changes in density, viscosity, free volume, and intermolecular cohesion. Parameters such as ultrasonic velocity, attenuation, and derived acoustic constants (Rao's constant, Wada constant, Van der Waals constant) provide indirect yet precise information about the molecular structure and thermodynamic state of the oil. Unlike chemical methods, ultrasonic techniques are nondestructive, require minimal sample preparation, and can be implemented for continuous monitoring **[11-17]**.

Previous studies have demonstrated the correlation between ultrasonic velocity and thermal expansion, viscosity reduction, and dielectric strength in insulating fluids. However, systematic investigations that integrate experimental measurements with calculated thermo-physical parameters—such as free volume, molar volume, and surface tension—remain limited. Such comprehensive analysis is essential for establishing ultrasonic diagnostics as a reliable predictive tool for transformer oil aging and performance assessment **[18-26]**.

The present work addresses this gap by conducting a detailed ultrasonic study of transformer oils at different temperatures and service ages. Experimental measurements of density, viscosity, and ultrasonic velocity are complemented by calculated values of free volume, acoustic constants, and surface tension. The objective is to evaluate the combined influence of thermal stress and aging on oil properties and to establish ultrasonic evaluation as a nondestructive methodology for transformer oil diagnostics **[27-36]**. This approach not only enhances understanding of molecular interactions in insulating liquids but also provides a scientific basis for predictive maintenance strategies in power systems.

II. MATERIALS AND METHODS

Three transformer oil samples were selected for the study:

TO1: Fresh, unused power transformer oil.

TO2: One year used transformer oil collected from an operational transformer.

TO3: Two year used transformer oil collected from the same transformer after extended service.

Each sample was filtered through fine mesh to remove suspended impurities and moisture traces. The oils were stored in airtight glass containers to prevent oxidation and contamination before testing. All measurements were performed under controlled laboratory conditions.

The experimental investigations were carried out using a variable temperature ultrasonic interferometer operating at a fixed frequency of 2 MHz. The setup consisted of a high precision crystal transducer, a thermostatically controlled water bath, and a digital temperature controller with an accuracy of ±0.1 K. The interferometer was calibrated using standard liquids (distilled water and benzene) to ensure measurement accuracy.

Temperature was varied from 303 K to 333 K in steps of 10 K. For each temperature, the following parameters were measured:

Density (ρ): Determined using a calibrated pycnometer.

Viscosity (η): Measured using an Ostwald viscometer.

Ultrasonic velocity (V): Obtained directly from the interferometer using the relation

$$V=2n\cdot f$$

Where, n is the number of fringes counted and f is the frequency of the ultrasonic wave.

Ultrasonic velocity measurements were made using an ultrasonic interferometer (Model M-84, supplied by M/S Mittal Enterprises, New Delhi) at 4 MHz with the accuracy of ±0.1 $m \cdot s^{-1}$. The measuring cell of an interferometer is a specially designed double- walled vessel with provision for temperature constancy. An electronically operated digital constant temperature bath (Model SSI-03 Spl, supplied by M/S Mittal Enterprises, New Delhi), operating in the temperature range of −10°C to 85°C with an accuracy of ±0.1°C has been used to circulate water through the outer jacket of the double-walled measuring cell containing the transformer oil.

All measurements were repeated thrice to ensure reproducibility, and mean values were used for analysis. The data were tabulated (Tables 1–4) and plotted to visualize temperature dependent trends. Comparative analysis among TO1, TO2, and TO3 was performed to assess the influence of aging on thermo-physical and acoustic properties. Statistical deviations were within ±1.5 %, confirming high experimental precision.

The obtained results were compared with literature values for standard transformer oils to validate consistency. Observed trends—such as decreasing viscosity and ultrasonic velocity with temperature and aging were interpreted in terms of molecular expansion, free volume increase, and weakening of cohesive forces. The correlation between ultrasonic velocity and surface tension was used to establish the diagnostic potential of ultrasonic evaluation for transformer oil health monitoring.

III. THEORY

The following thermodynamic parameters were calculated from measured values of density, viscosity and ultrasonic velocity.

(i) Free Volume (V_f): Free volume is one of the significant factors in explaining the variations in the physio-chemical properties of liquids and liquid mixtures, which depends on the Shape, size, and structural arrangements of molecules in the mixture. [21] Free volume can be calculated by using the measured values of ultrasonic velocity (U) and the viscosity (η) of liquid [22] as follows

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

Where, 'M_{eff}' is the effective molecular weight, (M_{eff} = in which Mi and Xi are the molecular weight and the mole fraction of the individual constituents respectively), 'K' is a dimensionless constant independent of temperature and liquid. Its value is 4.281 x 10^9 [23].

(ii)Available Volume (V_a): Available volume is the direct measure of compactness and strength of binding between the molecules of a liquid or liquid mixtures. Schaff's et al [21, 27] shown that the available volume can be obtained by the relation.

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

U_∞= the Schaaf's limiting value taken as 1600 m/s for liquid mixture and U= Ultrasonic velocity of the mixture.

(iii)Molar Volume (V_m): It is calculated by using the formula

$$V = M/\rho,$$

Where M = Mol. weight of mixture

(iv)Rao's constant (R): Rao's constant is also known as molar sound velocity and it is an additive property and can be evaluated by an equation given by Bagchi et al.

(v)Wada's constant (W): Wada's constant also known as Molar compressibility is dependent on adiabatic compressibility and density is given by

(vi)Vander wall's constant: It is estimated from the molar volume and cohesive energy density, reflecting intermolecular attraction.

$$b = (M/\rho).[1-(RT/MU^2).\{[1+(MU^2 /3RT)]^{1/2} - 1\}]$$

(vii) Surface tension (S): Surface tension can be calculated by using the relation

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$$S = k \cdot \eta \cdot V/\rho$$

IV. RESULTS 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, Table-3, and Table-4. Variation of some parameters with temperatures are shown in fig-1 to fig.-7.

Table-1: Experimental values of density, viscosity and ultrasonic velocity at different Temperatures.

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	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	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	833.67	828.03	821.62	818.37	14.293	11.513	9.789	8.356	1361.6	1345.2	1320.4	1296.4

Table-2: Calculated values of Free Volume, Available volume, and Molar Volume at different temperatures.

Power Transformer Oil	Free Volume				Available volume				Molar Volume			
	303	313	323	333	303	313	323	333	303	313	323	333
TO-1	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	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	0.074	0.100	0.124	0.153	0.030	0.033	0.036	0.039	0.204	0.206	0.207	0.208

Table-3: Calculated values of Rao's Constant, Wada Constant and Van der Waals' constant at different temperatures.

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	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	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	2.263	2.270	2.273	2.268	0.1564	0.1568	0.1570	0.1567	0.1863	0.1848	0.1841	0.1828

Table-4: Calculated value of Surface tension at different temperatures.

Power Transformer Oil	Surface tension			
	303	313	323	333
TO-1	26708.11	25795.54	24981.68	24176.68
TO-2	26126.14	25452.86	24618.58	23649.49
TO-3	26388.16	25737.53	24835.32	24065.72

The thermo-physical and acoustic parameters of transformer oils TO1, TO2, and TO3 were analyzed to understand the influence of temperature and aging on their molecular structure and dielectric performance. The results reveal consistent trends across all measured and derived properties, reflecting the interplay between thermal expansion, viscosity reduction, and weakening of intermolecular forces.

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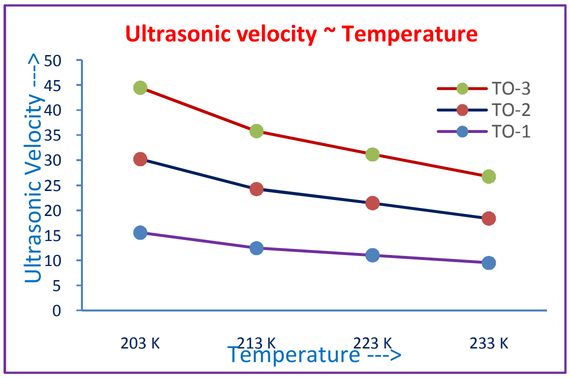

Figure-1: Variation of ultrasonic velocity with temperature.

The decrease in density with temperature observed for all samples is attributed to thermal expansion, which increases intermolecular spacing and reduces mass per unit volume. The higher density of TO3 compared to TO1 and TO2 suggests the presence of oxidation products and polar contaminants formed during prolonged service. Viscosity exhibits an exponential decline with temperature, typical of liquids whose molecular mobility increases with thermal energy. The viscosity–temperature relationship (Figure 1) indicates that TO1 retains higher viscosity at lower temperatures, implying stronger cohesive forces and better lubrication properties. In contrast, TO3 shows a pronounced drop, confirming molecular degradation and chain scission during aging. Ultrasonic velocity decreases with temperature (Figure 2), reflecting reduced elasticity and cohesive energy of the medium. The velocity trend correlates inversely with free volume expansion, as higher temperatures and aging increase molecular spacing, thereby lowering the propagation speed of ultrasonic waves. The higher velocity in TO1 signifies greater structural uniformity and stronger intermolecular interactions.

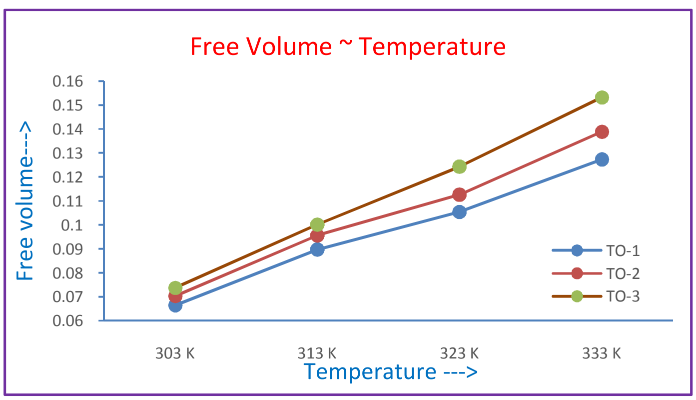

Figure-2: Variation of free volume with temperature.

The calculated free volume and available volume (Table 2) increase with temperature, consistent with molecular expansion and reduced packing efficiency. The largest free volume in TO3 indicates significant structural loosening due to oxidation and polymerization of degradation products. The nearly constant molar volume (~0.205–0.209 $m^3 mol^{-1}$) across all samples suggests that molecular size remains unchanged, but the spatial arrangement becomes less compact with aging. This expansion of free volume directly influences viscosity and ultrasonic velocity, confirming that molecular disorder and reduced cohesive forces are dominant factors in aged oils.

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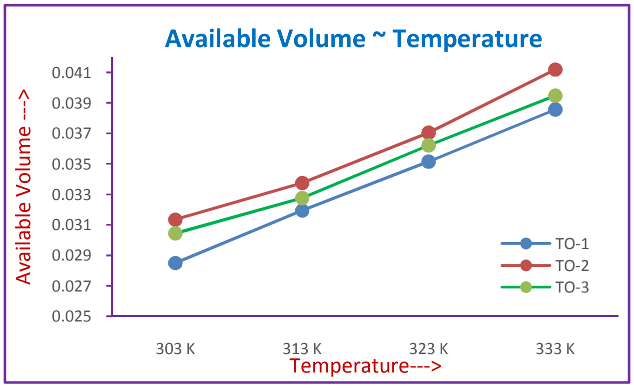

Figure-3: Variation of available volume with temperature

Rao's constant and Wada constant (Table 3) provide insight into the acoustic and thermodynamic behavior of the oils. Rao's constant, which relates to molecular polarizability, decreases slightly with aging, indicating reduced cohesive energy and dielectric strength. The Wada constant remains nearly invariant with temperature, suggesting minimal change in compressibility. The Van der Waals constant shows a clear decline with temperature and aging (Figure 3), signifying weakened intermolecular attractions. This reduction is consistent with the observed decrease in ultrasonic velocity and surface tension, confirming that molecular cohesion diminishes as the oil undergoes thermal and oxidative stress.

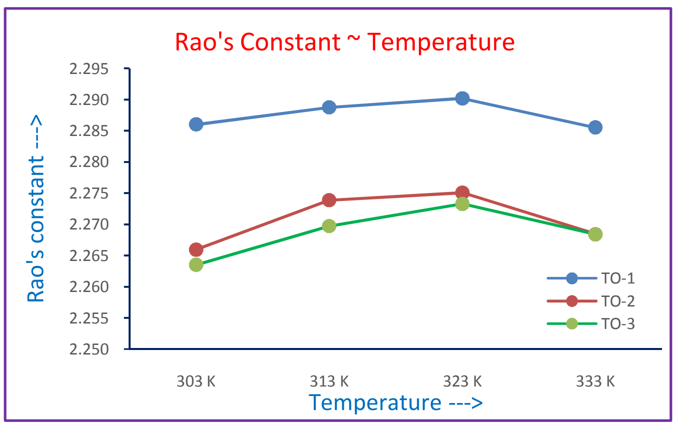

Figure-4: Variation of Rao's constant with temperature.

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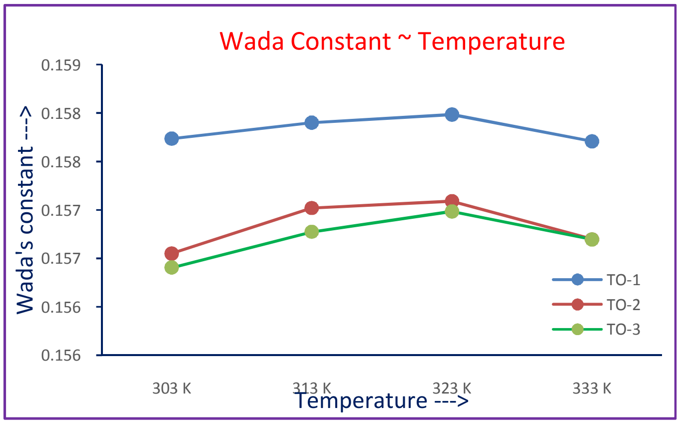

Figure-5: Variation of Wada's constant with temperature.

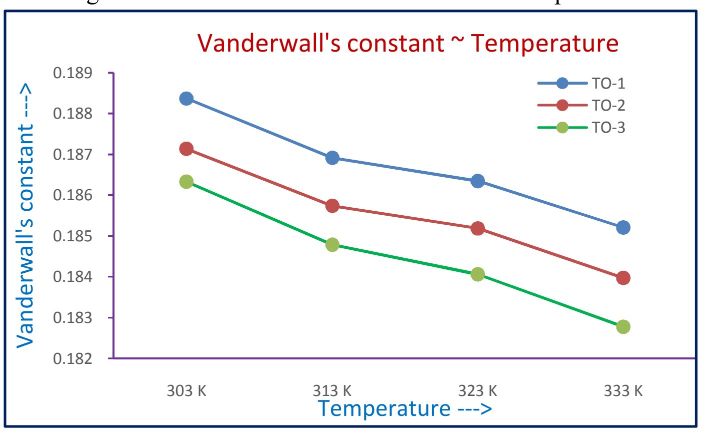

Figure-6: Variation of Vander wall's constant with temperature.

Surface tension values (Table 4, Figure 4) decrease with temperature for all oils, reflecting the reduction in cohesive forces at the liquid surface. TO1 exhibits the highest surface tension, indicative of strong intermolecular bonding and purity. TO2 and TO3 show lower values, which can be attributed to the accumulation of polar degradation products and impurities that disrupt molecular alignment at the interface.

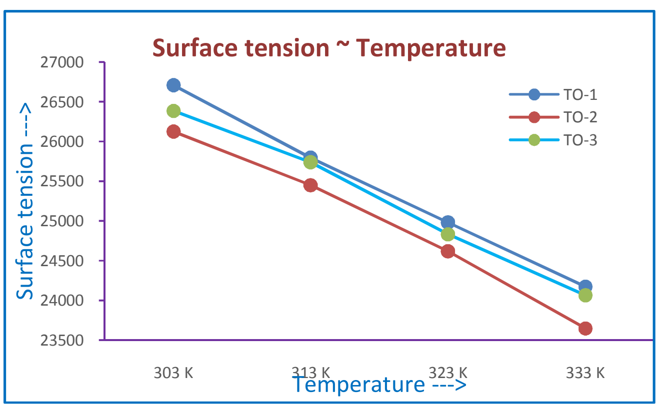

Figure-7: Variation of surface tension constant with temperature.

The decline in surface tension with aging is a critical indicator of reduced insulating performance, as it correlates with the weakening of molecular cohesion and the formation of oxidation byproducts that compromise dielectric stability.

The combined analysis of experimental and derived parameters reveals a coherent pattern: increasing temperature and prolonged service both lead to molecular expansion, reduced viscosity, lower ultrasonic velocity, and diminished surface tension. These changes are accompanied by a decrease in acoustic and thermodynamic constants, confirming the progressive weakening of intermolecular forces. Among the samples, TO1 (fresh oil) demonstrates superior stability and cohesive strength, TO2 (one year used oil) shows moderate degradation, and TO3 (two year used oil) exhibits pronounced deterioration. The correlation between free volume expansion and the decline in ultrasonic velocity and surface tension provides a quantitative measure of oil aging and degradation.

The observed trends highlight the potential of ultrasonic and thermo-physical measurements as diagnostic tools for assessing transformer oil health. Monitoring parameters such as ultrasonic velocity, viscosity, and surface tension can provide early indications of molecular degradation and loss of dielectric integrity. The integration of acoustic constants (Rao's and Wada) with volumetric parameters offers a comprehensive framework for evaluating oil performance under thermal stress and aging conditions.

V. CONCLUSION OF DISCUSSION

The present study systematically investigated the thermo-physical and acoustic behavior of transformer oils (TO1, TO2, and TO3) over the temperature range of 303–333 K. The experimental and calculated parameters—including density, viscosity, ultrasonic velocity, free volume, Rao's constant, Wada constant, Van der Waals constant, and surface tension—collectively reveal the influence of temperature and aging on the molecular structure and dielectric performance of transformer oils.

All oils exhibited the expected thermal trends: decreasing density, viscosity, ultrasonic velocity, and surface tension with increasing temperature, accompanied by an increase in free and available volumes. These variations are attributed to thermal expansion and the consequent reduction in intermolecular cohesion. The acoustic and thermodynamic constants further confirm that molecular interactions weaken with both temperature and service aging.

Among the samples, TO1 (fresh oil) demonstrated superior stability, maintaining higher viscosity, ultrasonic velocity, and surface tension, along with lower free volume. TO2 (one year used oil) showed moderate degradation, while TO3 (two year used oil) exhibited significant deterioration in physical and acoustic properties. The correlation between free volume expansion and the decline in ultrasonic velocity and surface tension provides a quantitative measure of oil aging.

The findings emphasize that ultrasonic and thermo-physical parameters can serve as reliable diagnostic indicators for transformer oil condition monitoring. Regular assessment of these properties enables early detection of molecular degradation, ensuring timely maintenance and replacement to preserve transformer efficiency and insulation reliability. This approach offers a scientific basis for predictive maintenance strategies in power systems.

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