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Temperature Effects on Transformer Oil Assessed by Ultrasonic Techniques

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Abstract: *This paper presents a comprehensive ultrasonic investigation of power transformer oil across a controlled temperature range. Ultrasonic velocity, density and viscosity were measured using a ultrasonic technique. Various thermo-acoustic parameters were calculated using these values. The study reveals a linear decrease in ultrasonic velocity with increasing temperature, accompanied by a decrease in density and viscosity. These findings demonstrate the sensitivity of ultrasonic methods to thermal effects and highlight their potential for real-time monitoring of transformer oil quality and aging.*

Keywords: Transformer oil, Ultrasonic velocity, Temperature dependence, relaxation time, Non-destructive testing

I. INTRODUCTION

Transformer oil plays a dual role: electrical insulation and thermal management. Its reliability is crucial for the safe operation of power transformers. Traditional diagnostic methods—such as dissolved gas analysis (DGA) and dielectric breakdown testing—are effective but often invasive, time-consuming, and require sample extraction.

Ultrasonic techniques, by contrast, are non-destructive, rapid, and capable of in-situ monitoring. Ultrasonic waves interact with the medium's molecular structure, making them sensitive to changes in density, viscosity, and chemical composition. This study focuses on the temperature dependence of ultrasonic parameters in transformer oil, aiming to establish a diagnostic framework for predictive maintenance. In this paper, we measure**,** ultrasonic velocity, viscosity and density in transformer oil at different temperatures. Establish correlations between ultrasonic parameters and physical properties. Evaluate ultrasonic methods as predictive tools for transformer oil degradation.

II. MATERIALS AND METHODS

In the present study, three commercial mineral-based transformer oil (naphthenic type) were studied, labelled as follows:

TO1: Fresh (unused) transformer oil, which was manufactured in the year 2023.
TO2: 1 year used transformer oil manufactured in the year 2021
TO3: 2 year used transformer oil manufactured in the year 2019.
All the samples are branded in India, as IS-335: 1993.

The density, viscosity and ultrasonic velocity were measured at different temperatures. 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. The viscosity of all the samples were measured by LOVIS-2000 M/ME of Anton Parr make suited for liquids of low viscosity at different temperatures, which work on rolling ball principle.

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The density of all the samples were measured by Anton-Parr DSA5000M Density meter having oscillating U- tube. An inbuilt Peltier thermostat maintained the temperature of the U-tube.

III. THEORY

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

Adiabatic Compressibility (β): The adiabatic compressibility is the fractional decrease of volume per unit increase of pressure when no heat flows in to or out of the system. It is calculated from the ultrasonic velocity (U) in ms^{-1} and the density (ρ) in $Kg.m^{-3}$ of the medium by using the equation of Newton Laplace [18] as,

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

Intermolecular free length (L_f): The intermolecular free length is the distance between the surfaces of the neighbouring molecules. It is calculated by using the relation [19],

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

Where 'K_T" is the temperature-dependent constant called as Jacobson's constant {K_T=93.875+0.375T) $X10^{-8}$} [20] T is the absolute temperature and 'β' is the adiabatic compressibility.

Relaxation time (τ): Relaxation time is the time taken for the excitation energy to appear as translational energy and it depends on temperature and impurities. The relaxation time can be calculated from the relation,

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

Internal Pressure (π_i): The measurement of internal pressure is important in the study of the thermodynamic properties of liquids. The internal pressure is the cohesive force, which is a resultant of force of attraction and force of repulsion between the molecules. It is calculated by using the relation [24],

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

Where, 'b' stands for cubic packing, which is assumed to be '2' for all liquids, 'R' is the Universal gas constant, 'η' is the viscosity of solution in $N.S.m^{-2}$.

Acoustic impedance (Z): Acoustic impedance is a measure of the ease with which a sound wave propagates through a particular medium and relates to the elastic properties of medium [25-26]. The acoustic impedance is given by,

$$Z = U.\rho$$

(vii) Gibb's free energy (ΔG): The change in Gibb's free energy is calculated by using the relation

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

Where 'k' is Boltzmann's constant and '*h*' is Planck's constant.

IV. RESULTS

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 parameters with temperatures are shown in fig-1 to fig.-6.

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(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

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TABLE-2: Calculated values of adiabatic Compressibility, relaxation time and free length at different temperatures.

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

TABLE-3: Calculated values of Acoustic impedance, Gibbs free energy and Internal Pressure at different temperatures.

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

V. DISCUSSION

Variations of different thermo-acoustic parameters with temperatures are as shown in figure-1 to Figure-6

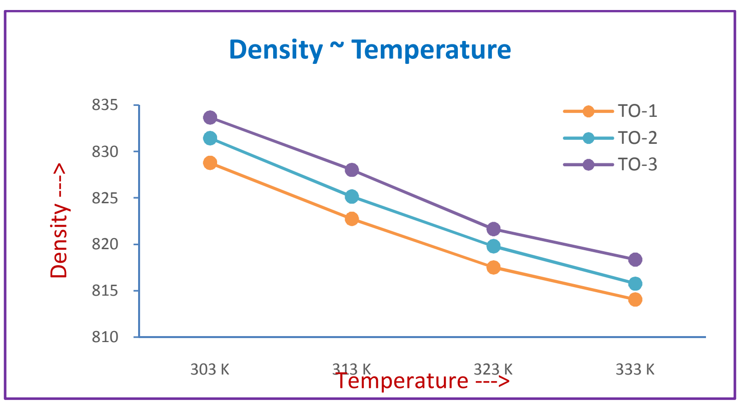

Figure-1: Variation of Density with Temperature

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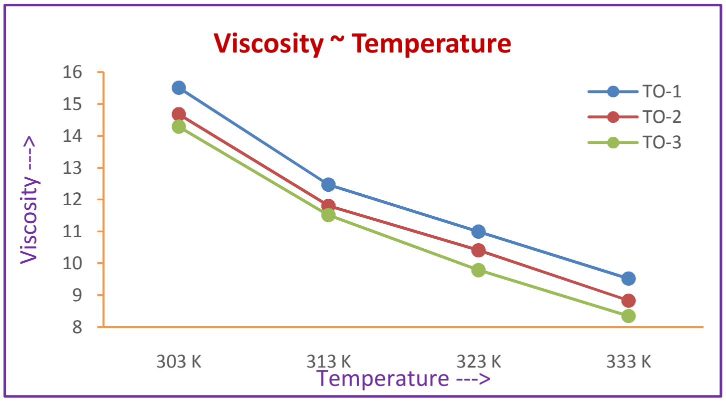

Figure-2: Variation of Viscosity with Temperature

The experimental and derived parameters presented in Tables 1 and 2 provide significant insights into the physicochemical and acoustic behavior of transformer oils under varying thermal conditions and service durations. The systematic variation of density, viscosity, and ultrasonic velocity with temperature, coupled with the calculated adiabatic compressibility, relaxation time, and free length, highlights both the intrinsic thermal response of the oils and the progressive changes induced by aging.

Density values for all samples decrease monotonically with increasing temperature, consistent with thermal expansion of the liquid phase. Notably, aged oils (TO-2 and TO-3) exhibit slightly higher densities compared to the pure sample (TO-1), which can be attributed to oxidative degradation and accumulation of polar by-products during service. Viscosity shows a pronounced decline with temperature, reflecting reduced intermolecular cohesion at elevated thermal energies. The pure oil demonstrates the highest viscosity at lower temperatures, whereas the two-year used oil (TO-3) exhibits the lowest viscosity at higher temperatures, suggesting that aging reduces molecular weight distribution and enhances fluidity.

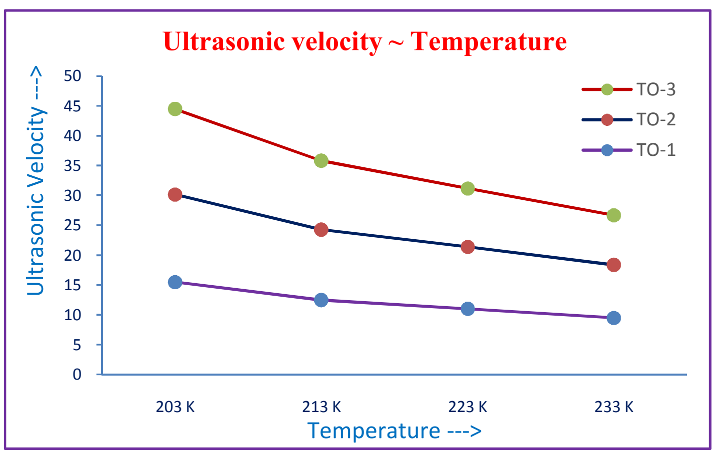

Figure-3: Variation of ultrasonic velocity with temperature

Ultrasonic velocity decreases with temperature across all samples, indicating reduced elastic stiffness of the medium. The pure oil consistently maintains higher velocities, while aged oils show progressive reductions, particularly TO-3. This decline is indicative of structural weakening and increased free volume within the liquid matrix due to aging.

The calculated compressibility values increase with temperature, confirming that the oils become more compressible as molecular spacing expands. Among the samples, TO-2 exhibits the highest compressibility, reflecting diminished

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elasticity and structural integrity after one year of service. The pure oil retains the lowest compressibility, underscoring its superior resistance to deformation under acoustic stress.

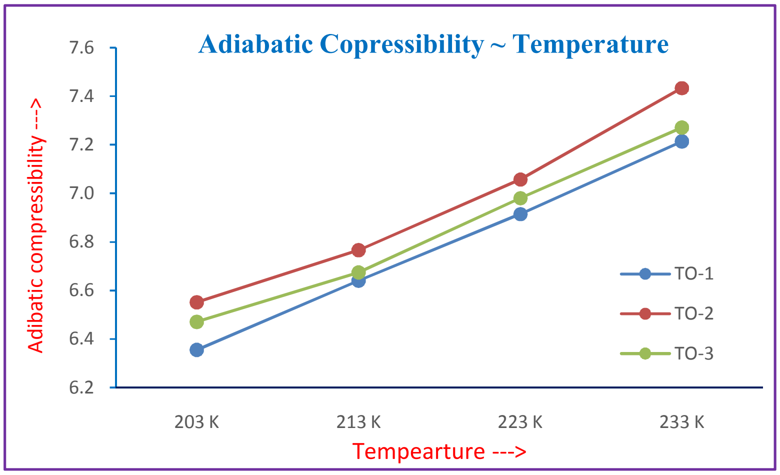

Figure-4: Variation of adiabatic compressibility with temperature

The free length parameter, which represents the average intermolecular spacing, increases with temperature as expected. The pure oil consistently exhibits the lowest free length, suggesting tighter molecular packing and greater structural stability. Aged oils, particularly TO-2, show higher free lengths, reflecting increased molecular separation and reduced compactness.

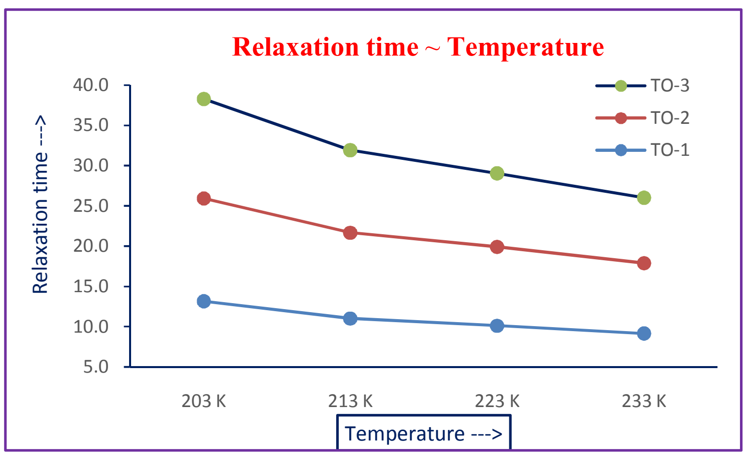

Figure-5: Variation of relaxation time with temperature

Relaxation time decreases with temperature for all oils, signifying faster molecular reorientation at elevated thermal energies. The pure oil demonstrates longer relaxation times, indicative of stronger intermolecular interactions and slower relaxation dynamics. In contrast, TO-3 shows the shortest relaxation times, consistent with weakened molecular cohesion and enhanced disorder due to prolonged aging.

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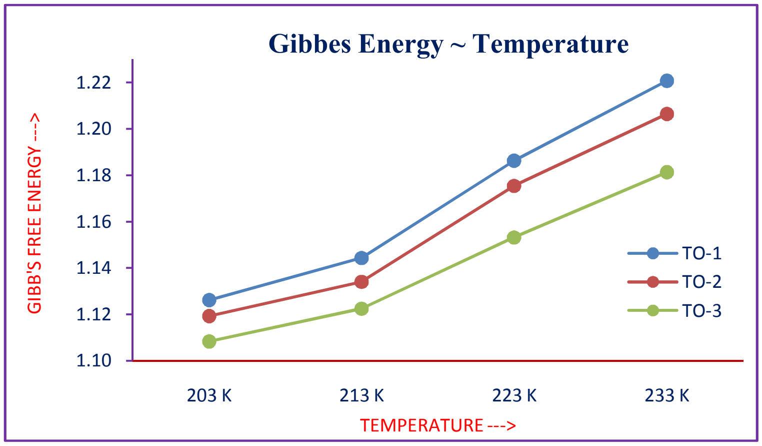

Figure-6: Variation of Gibbs' free energy with temperature

The comparative analysis clearly demonstrates that aging induces measurable changes in both experimental and derived parameters. Increased density, reduced viscosity, lower ultrasonic velocity, higher compressibility, shorter relaxation times, and longer free lengths collectively point to degradation of the oil's physicochemical and acoustic properties. These changes are consistent with oxidative aging, contamination, and breakdown of long-chain hydrocarbons, which compromise the oil's insulating and cooling performance in transformers.

The combined evaluation of thermal and aging effects reveals that transformer oils undergo progressive deterioration in structural integrity and acoustic stability with service duration. The pure oil (TO-1) exhibits superior performance across all parameters, while TO-3 (two-year used oil) shows the most pronounced degradation. These findings underscore the importance of regular monitoring of acoustic and physicochemical properties as diagnostic tools for assessing transformer oil health and predicting service life.

The acoustic and thermodynamic parameters presented in Table-3 provide further evidence of the structural and energetic changes occurring in transformer oils under thermal stress and service aging. These parameters, when analyzed alongside density, viscosity, ultrasonic velocity, compressibility, relaxation time, and free length, offer a holistic view of the oil's physicochemical and acoustic behavior.

Acoustic impedance decreases with increasing temperature for all samples, reflecting the combined effect of reduced density and ultrasonic velocity. The pure oil (TO-1) consistently exhibits higher impedance values compared to aged oils, indicating stronger molecular cohesion and better resistance to acoustic transmission. In contrast, TO-2 and TO-3 show progressively lower impedance, confirming that aging reduces the oil's ability to transmit ultrasonic waves effectively. This decline is consistent with the observed increase in compressibility and free length, reinforcing the weakening of intermolecular interactions.

The Gibbs free energy values increase with temperature, signifying enhanced molecular disorder and reduced thermodynamic stability at elevated thermal levels. TO-1 demonstrates higher ΔG values across all temperatures, suggesting greater resistance to spontaneous degradation and chemical reactions. Aged oils, particularly TO-3, exhibit lower ΔG values, indicating diminished stability and higher susceptibility to oxidative processes. This trend highlights the role of Gibbs free energy as a thermodynamic marker of oil aging and degradation.

Internal pressure decreases with temperature for all oils, as thermal expansion reduces cohesive forces between molecules. TO-1 maintains the highest internal pressure values, reflecting stronger intermolecular interactions and compact molecular packing. TO-3 shows the lowest values, underscoring significant deterioration in molecular cohesion due to prolonged service aging. The progressive decline in internal pressure with aging is consistent with the observed reduction in viscosity and ultrasonic velocity, confirming the loss of structural compactness and stability.

The combined analysis of acoustic impedance, Gibbs free energy, and internal pressure reveals that both temperature and aging exert a profound influence on the thermodynamic and acoustic properties of transformer oils. Pure oil exhibits superior stability, compactness, and resistance to acoustic transmission, while aged oils show progressive deterioration in all parameters. These findings align with the trends observed in earlier tables-1 and table-2, establishing a coherent picture of transformer oil degradation.

VI. CONCLUSION

The present study demonstrates that transformer oils exhibit systematic variations in their physicochemical and acoustic properties with both temperature and service duration. Experimental measurements revealed that density, viscosity, and ultrasonic velocity decrease with increasing temperature, while derived parameters such as adiabatic compressibility and free length increase, and relaxation time decreases. These thermal trends are consistent with the expected molecular dynamics of hydrocarbon liquids under heating.

Comparative analysis between pure and aged oils highlights the impact of service aging: used oils show higher densities, lower viscosities, reduced ultrasonic velocities, greater compressibility, shorter relaxation times, and longer free lengths. Collectively, these changes indicate progressive deterioration in structural integrity and acoustic stability, attributable to oxidative degradation and contamination during transformer operation. Among the samples, TO-1 (pure oil) exhibited superior stability, whereas TO-3 (two-year used oil) showed the most pronounced degradation.

Overall, the results confirm that ultrasonic and physicochemical measurements provide reliable diagnostic indicators of transformer oil health. Regular monitoring of these parameters can serve as an effective tool for assessing aging, predicting service life, and ensuring the safe and efficient performance of power transformers.

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