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Characterisation and Analysis of Used Lubrication Oil: Implications for Performance and Efficiency

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Abstract

The present work demonstrates a two-step process for effectively recovering and restoring used SAE 20W40 lubricating oil through thermal vacuum distillation and chemical treatment with Zinc Dialkyl Dithiophosphate (ZDDP). The vacuum distillation process removes moisture, volatiles and degraded fractions, and the ZDDP additive replaces broken-down anti-wear and oxidative stability characteristics. Untreated, treated, and virgin oils underwent a complete physicochemical characterisation including density, viscosity, viscosity index, flash point, fire point, pour point, specific gravity and Total Acid Number. This indicates that the physicochemical properties of the treated oil were like those of the commercial SAE 20W40 oil. Among them, the Total Acid Number decreased from more than 10 to 2 mg KOH/g, while the viscosity index experienced a significant improvement. In addition, an economic analysis of costs estimated the treatment process to be cost-effective at approximately 25-40 % lower cost per litre than virgin oil at market rates. This demonstrates the viability and sustainability of the re-refinement integrated into industrial uses and the recovery of lubricants from municipalities.

Major Findings: *The two-stage treatment enhanced performance by increasing viscosity from 167 cP to 266 cP and raising the viscosity index from 51 to 81. TAN decreased from >10 to ~2 mg KOH/g, indicating improved chemical stability. Enhanced flash/fire points and a reduced pour point (–18 °C) confirm suitability for extreme thermal conditions.*

Keywords: *Dehydration, Treated Lubricating Oil, Untreated Lubricating Oil, Vacuum Distillation, Virgin Lubricating Oil, Zinc Dialkyl Dithiophosphate*

1.0 Introduction

A gradual rise in the demand for energy and modes of transportation has entailed a relative rise in petroleum-based lubricating oils globally and particularly in cars and heavy machinery products. Combinations of engine oils SAE 20W40 (Multigrade engine oils) are nowadays considered invaluable in the needs of current internal combustion engines, crushing the choice of providing a large level of operational viscosity, serving to a minimal measure of metal-to-metal cooperation, and alluring simplicity in gravity to thermal and oxidative in opposition to scorching conditions and severe loading[1]. But since they are exposed to long service life, these lubricants experience gradual chemical and mechanical wear-out[2]. Subjected to high levels of operating temperatures, shear stress, ambient air, combustion products, and particulate contamination, they begin changing at the molecular level over time. The consequences of these changes consist of the viscosity breakdown, loss of additives, the rise in the level of acidity, the sludge and varnish-forming residue accumulation, and the general loss in lubricating

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power[3]. Consequently, the oil used ceases to conform to OEM specifications and must be disposed of or recycled.

The disposal practices for used lubricating oil in many developing regions remain grossly inadequate, with significant volumes being discarded into the open environment, soil, drainage systems, or water bodies without any prior treatment or containment[4]. The release of hazardous substances, including heavy metals (e.g., lead, cadmium, chromium), Polycyclic Aromatic Hydrocarbons (PAHs), and oxidised degradation products, occurs due to this practice, which creates severe threats to ecological systems and public health[5]. The life-cycle perspective demands that spent lubricating oil should not be treated as waste but recognised as a valuable secondary resource. The base oil component, which makes up 70–80 % of used oil, can be recovered through proper treatment to be reused, thus minimising environmental impact and production costs of fresh lubricants. The re-refining process of used oil into base oil for re-blending with additives presents itself as a technically viable and environmentally sustainable solution. Thermal vacuum distillation stands out among different re-refining techniques because it offers low environmental impact and operational simplicity while effectively removing water and light hydrocarbons and thermally unstable constituents without requiring aggressive chemicals or high-pressure hydrogenation systems[6].

In automobiles, lubricating oils are typically changed every 5,000 kilometres. Over time, engine oil undergoes degradation in key properties such as viscosity, specific gravity, flash point, and pour point are mainly influenced by constant exposure to high temperatures. The breakdown of additives results in sludge formation, combined with metal particles from engine wear, and water enters the oil through combustion processes[7]. Eventually, the oil loses its effectiveness and must be replaced. Although used lubricating oil accounts for a small share of total petroleum waste, it poses a significant threat to the environment. Consequently, recycling has become an effective solution for managing and treating used oil[8]. Although limited studies have focused on used engine oil, it has been found that the refined oil produced through the acid/clay treatment process contains higher acid content, which can lead to corrosion, leading to premature wear and a shorter lifespan of automobile engines[9]. When used engine oil is discarded irresponsibly, such as being dumped on land or in waterways, it poses a major threat to soil and groundwater quality[10]. When used as fuel, waste engine oil can generate harmful emissions[11]. However, refining it serves as a more environmentally friendly and financially beneficial alternative method for refining used oil, including vacuum distillation and hydrogenation[12,13].

Although there is an increasing interest in the recovery and reuse of spent lubricating oils, there is still a lack of coherence in the available body of research concerning the reclamation of the oils back to the SAE-grade quality levels. Although previous studies have already considered vacuum distillation as a single re-refining technology, they have mostly evaluated how either recovery efficiency or clean-up occurs rather than the importance of additive replenishment in restoring tribological and oxidative properties. On the other hand, studies focusing on additive chemistry, especially that which involves Zinc Dialkyl Dithiophosphate (ZDDP), will apply such formulation to virgin base oils as opposed to thermally recovered oils, resulting in a practical gap in real-world implementation. Additionally, there are rarely reported comparative assessments of untreated, thermally re-refined, and chemically re-refined oils under uniform test conditions, and therefore, it is hard to count on the efficiency of integrative recovery procedures. A lack of clarity and consistency in the process parameters, e.g., distillation temperatures, pressure control, ZDDP concentration, and mixing protocols, also lack of reproducibility and scalability. The study aims to fill these vital gaps by introducing the mechanism of a methodologically rigorous two-stage process of thermal distillation and ZDDP enhancement and subsequent comprehensive assessment of physicochemical properties against the reference virgin SAE 20W40 oil.

The research introduces a two-stage re-refinement approach which combines vacuum distillation with ZDDP additive treatment to achieve the restoration of used SAE 20W40 oil to near-virgin quality through experimental physicochemical benchmarking.

The present study aims to develop and test a sustainable laboratory-based method for extracting and revitalising used SAE 20W40 lubricating oil. The research implements a two-stage method, which starts with thermal vacuum distillation before applying ZDDP for chemical

enhancement. The research investigates how ZDDP functions to restore vital functional properties, including anti-wear performance, viscosity stability and oxidative resistance. The study performs detailed physicochemical tests of density and specific gravity, kinematic viscosity and viscosity index, and TAN to evaluate the treated oil against untreated and commercial SAE 20W40 oils. The research aims to determine if this combined treatment method can become a reliable and expandable solution for industrial lubricant recycling with reduced environmental effects.

2.0 Materials and Methods

2.1 Materials

The main base stock in this research consisted of SAE 20W40 lubricating oil purchased from a local automotive service centre in its unaltered state. The selected base stock represents the typical waste oil materials which appear in industrial and transport sectors. The chemical additive used for post-treatment consisted of ZDDP, which Merck Chemicals provided at >98% purity. The researchers chose ZDDP because it functions as a multi-purpose additive which protects against wear and corrosion while acting as an antioxidant in lubricant formulations. All analytical procedures required solvents, titrants, and reagents, which were analytical grade and obtained from Sigma-Aldrich. The used lubricating oil is shown in Figure 1. The structural representation of ZDDP is shown in Figure 2.



Figure 1. The photographic view of untreated lubricating oil.

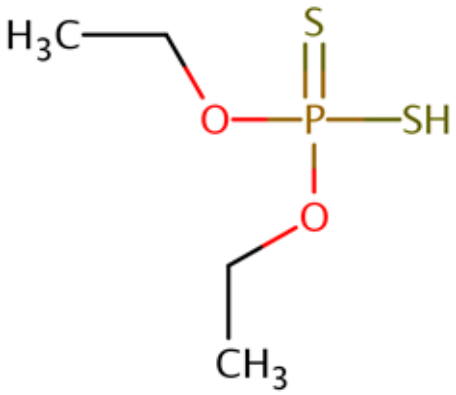


Figure 2. The structural representation of Zinc Dialkyl Dithiophosphate.

2.2 Pre-treatment: Dehydration of Used Lubricating Oil

The first step in the process involved dehydration of untreated SAE 20W40 oil to remove water that could interfere with distillation and affect the stability of additives. The oil was heated in a stainless-steel reactor

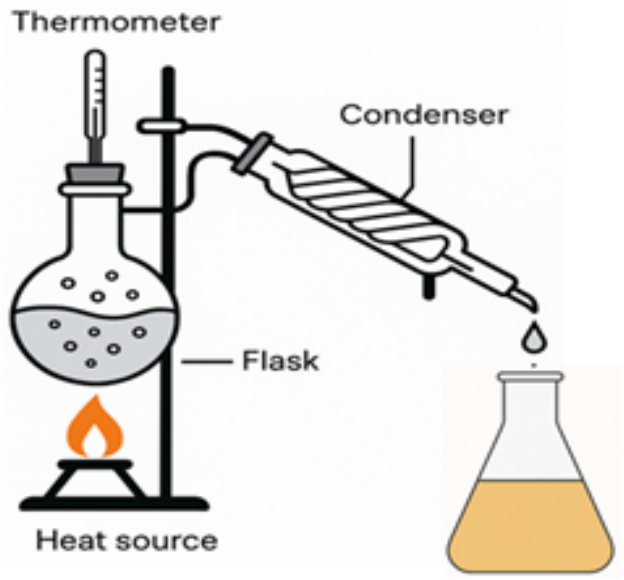


Figure 3. Laboratory distillation apparatus used for the dehydration and thermal distillation pre-treatment.

equipped with a mechanical stirrer and a digital temperature controller. The heating was maintained at 120 ± 2 °C for approximately 45 minutes, with continuous stirring at 300 rpm. The dehydration endpoint was visually confirmed by the absence of bubbling and was further verified by maintaining the temperature without any observable phase change. The laboratory distillation apparatus used for the dehydration and thermal distillation pre-treatment is shown in Figure 3.

2.3 Vacuum Distillation Process

The oil underwent vacuum distillation processing after dehydration to eliminate light fractions and degraded hydrocarbons. A three-necked round-bottom flask with a Liebig condenser and thermocouple operated as part of a vacuum distillation system that used a rotary vacuum pump to achieve base pressures of 20 mm Hg. The oil underwent a temperature increase to 240 ± 5 °C to enable the controlled separation of volatile compounds with low molecular weights and unstable thermal substances. The re-refining operation continued for 1.5 hours until the distillate collection reached its maximum point, and the residue achieved a uniform visual appearance. The refined base oil underwent vacuum cooling to prevent oxidation from occurring.

2.4 Chemical Treatment with ZDDP Additive

The base oil underwent ZDDP treatment to recover its anti-wear and antioxidant properties. A 1.0 wt.% ZDDP dose was created through weight measurement, followed by blending the additive with the oil at room temperature. The mixture was stirred at 500 rpm magnetic stirring for thirty minutes to achieve uniform distribution of additive molecules throughout the oil matrix. The mixture required twelve hours of undisturbed time at ambient conditions to allow any remaining impurities to settle. The oil underwent vacuum filtration through a 0.45 µm PTFE membrane to produce a clear treated lubricant, which was ready for testing. The chemical treatment procedure is shown in Figure 4.

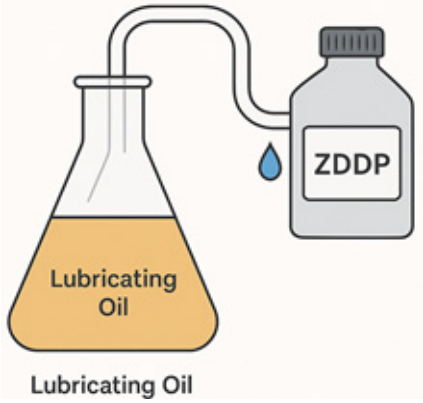


Figure 4. Chemical treatment of untreated lubricating oil.

2.5 Physicochemical Characterisation

To evaluate the efficacy of the refining and treatment process, the following physicochemical parameters were determined for untreated oil, treated oil, and standard SAE 20W40 oil:

Density and Specific Gravity: Measured at 15°C using a standard glass pycnometer by ASTM D1298. Measurements were repeated in triplicate and averaged.

Kinematic Viscosity: Determined at both 40°C and 100°C using Anton Paar SVM 3001 Viscometer, calibrated and operated as per ASTM D445. These temperatures reflect cold-start and high-temperature engine conditions, respectively.

Viscosity Index: Computed from the measured kinematic viscosities using the formula outlined in ASTM D2270, which provides an empirical measure of viscosity stability across the operational temperature range.

Total Acid Number (TAN): Estimated using potentiometric titration following ASTM D664 protocol. A solution of 0.1 N KOH in isopropanol was used as titrant, and the endpoint was determined by the inflexion point in millivolt readings. TAN serves as a critical indicator of oxidative degradation and corrosive potential.

2.6 Comparative Analysis

The collected test results were compared to both untreated waste oil and a commercially available virgin SAE 20W40 oil, which served as the performance standard. The extent of restoration in viscosity behaviour, acidity levels and thermal stability was evaluated through the re-refining and ZDDP treatment process. All reported results represent the average of three independently prepared



(a) **(b)**

Figure 5. **(a)** The treated, and **(b)** Virgin lubricating oil.

and tested samples to ensure reproducibility and reduce experimental variability. Minor deviations are expressed as standard error bars in the graphical data. Standard deviation was calculated where applicable to assess the reliability and consistency of the observed properties. The photographic view of treated and virgin lubricating oil is shown in Figure 5.

3.0 Results and Discussion

Figure 6 presents a comparative study of important physicochemical properties such as density, viscosity, viscosity index, flash point, fire point and cloud point for untreated lubricating oil, thermally treated oil enhanced with ZDDP and virgin SAE 20W40 oil. These parameters are essential in assessing the functional restoration and performance alignment of the re-refined oil in relation to standard commercial lubricants.

The evaluation of specific gravity, pour point, and TAN for untreated lubricating oil, thermally treated oil enhanced with ZDDP, and virgin SAE 20W40 oil is presented in Figure 7. These parameters are essential indicators of the oil's compositional stability, flow behaviour under low temperatures, and extent of oxidative degradation, respectively.

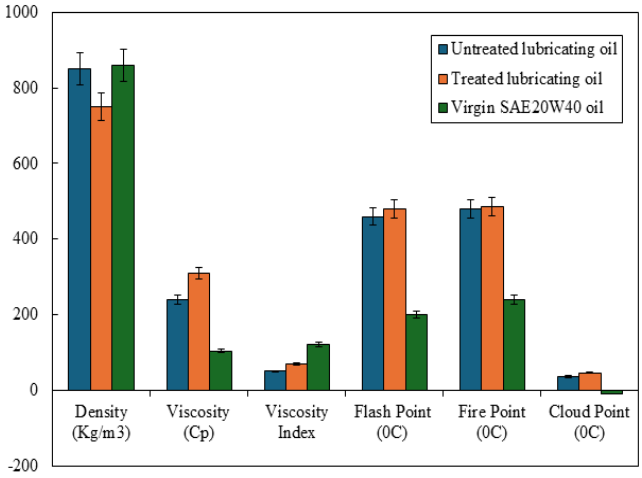


Figure 6. The variations of density, viscosity, viscosity index, flash point, fire point, and cloud point for untreated, treated and virgin lubricating oil.

3.1 Density

The density variations of the untreated, treated and virgin lubricating oil are shown in Figure 6. The untreated lubricating oil shows a density value that is slightly below both the treated oil and the virgin SAE 20W40 oil. The decrease in density is likely due to the formation of lighter degradation products and the loss of heavier base oil fractions during use[14]. The density of the treated oil

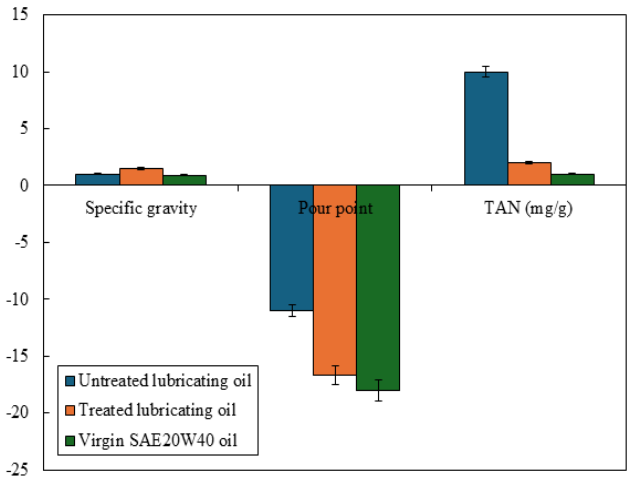


Figure 7. The evaluation of specific gravity, pour point, and TAN for untreated lubricating oil, thermally treated oil enhanced with ZDDP, and virgin SAE 20W40 oil.

after vacuum distillation and ZDDP treatment increases significantly to match the virgin oil density, indicating successful removal of volatile contaminants and some recovery of base oil components. The treated sample shows consistent density values, which confirm that the base stock composition remains intact and the molecular weight distribution is properly restored.

3.2 Viscosity

The viscosity variations of the untreated, treated and virgin lubricating oil are shown in Figure 6. The strength of lubricant films and their ability to bear loads depends heavily on viscosity. The untreated oil demonstrates average viscosity levels because it undergoes thermal breakdown and shear thinning throughout its operational period. The treated oil demonstrates a substantially higher viscosity level than both untreated and virgin oil samples[15]. The viscosity increase stems from oxidation products remaining in the oil and heavier fractions concentrating during distillation and potential ZDDP overdosing. High viscosity values improve load-carrying properties, but excessive levels can reduce both flowability and energy efficiency. The virgin oil maintains a viscosity level that falls within standard SAE 20W40 specifications (13-16 cP at 100°C), which indicates its refined and well-balanced composition.

3.3 Viscosity Index

The viscosity index variations of the untreated, treated and virgin lubricating oil are shown in Figure 6. The virgin SAE 20W40 oil exhibits the highest viscosity index among the three samples because it demonstrates superior temperature-viscosity stability. The treated oil demonstrates better temperature-dependent viscosity performance than the untreated oil, which indicates the additive's effectiveness in viscosity stabilisation[16]. ZDDP functions mainly as an anti-wear additive, yet its indirect role in viscosity index stabilisation occurs through its ability to prevent oxidative thinning. The untreated oil shows the lowest viscosity index value, which indicates its high susceptibility to viscosity degradation at high temperatures, thus demonstrating the importance of re-refining and restoring additives.

3.4 Flash Point

The flash point variations of the untreated, treated and virgin lubricating oil are shown in Figure 6. The flash point represents the minimum temperature at which oil vapours will ignite. The flash points of untreated and treated oils exceed those of virgin oil, even though this seems unexpected at first[17]. The distillation process removes light volatile compounds, which results in a higher flash point for the remaining residue. The treated oil contains heavier hydrocarbons and residual high-boiling fractions, which prevent the formation of flammable vapours at lower temperatures. The virgin oil maintains a standard flash point range of ~220°C because its volatile and base oil composition remains balanced, which results in its slightly lower value.

3.5 Fire Point

The fire point variations of the untreated, treated and virgin lubricating oil are shown in Figure 6. The fire point, which defines the temperature for oil to maintain combustion, shows a comparable pattern to the flash point. The fire points of untreated and treated oils exceed those of virgin oil. The vacuum distillation process of treated oil removes easily combustible fractions, which results in delayed sustained ignition[18]. The high thermal resistance of this oil indicates its heavy-end-rich composition, although it benefits applications requiring high temperatures. The virgin oil maintains an optimal fire point, which makes

it suitable for automotive applications because it balances volatility and stability.

3.6 Cloud Point

The cloud point variations of the untreated, treated and virgin lubricating oil are shown in Figure 6. The formation of wax crystals at the cloud point temperature affects the vehicle's ability to start in cold conditions. The virgin SAE 20W40 oil shows the lowest (most negative) cloud point value because it has better low-temperature flow properties and better refined wax content control. The untreated oil shows a much higher cloud point value, which indicates the formation of oxidised waxy compounds and the degradation of cold flow improvers[19]. The treated oil shows improvement but remains inferior to the virgin sample, indicating that vacuum distillation and additive treatment may not remove all crystallizable impurities or restore cold-weather performance to its original state. Future refinements may require the use of pour-point depressants or additional dewaxing processes.

3.7 Specific Gravity

The untreated oil shows a specific gravity that is slightly lower than both the treated and virgin SAE 20W40 oils, which indicates the formation of lighter degradation products and possible dilution effects due to volatile contaminants. After vacuum distillation, the treated oil shows a significant increase in specific gravity, which is very close to the value observed in the virgin sample (typically ~0.870–0.890 at 15.6°C). The increase in specific gravity can be attributed to the effective removal of volatile fractions and moisture, which concentrates the heavier hydrocarbon base stock[20]. The similarity between the treated and virgin oils suggests successful restoration of the oil's bulk density characteristics, which is crucial for maintaining hydrodynamic film formation in engine applications.

3.8 Pour Point

The pour point results demonstrate a significant improvement between untreated and treated oil because the treated sample achieved a pour point similar to virgin SAE 20W40 oil. The untreated oil shows a pour point at around –12°C because wax crystals form from the oxidation of long-chain hydrocarbons. The treated oil shows a significant reduction in pour point (near –18 to –20°C) because vacuum distillation effectively removed both high molecular weight paraffinic compounds and polar degradation products. The treated oil's improved pour point indicates that ZDDP addition did not compromise the oil's ability to flow well in cold temperatures. The virgin oil shows the lowest pour point value because its refined formulation and pour point depressants maintain excellent cold flow characteristics[21]. The treated oil and virgin oil show similar pour points, which demonstrates the re-refined oil's readiness for sub-ambient service applications, particularly in cold climate areas.

3.9 Total Acid Number

The untreated lubricating oil shows a TAN value greater than 10 mg KOH/g because of extensive oxidative degradation that produces acidic byproducts including carboxylic acids, phenols and sulfonates. The substances damage engine components while simultaneously accelerating the breakdown of the oil[22]. The distillation process effectively removes acidic volatiles and thermally unstable species from the treated oil, which results in TAN values approaching 2 mg KOH/g. The phosphorodithioate functionality in ZDDP acts to neutralise acids and protect against oxidation, which improves the chemical stability of the oil. The virgin oil maintains the lowest TAN value below 1 mg KOH/g because it follows standard industry formulations and has experienced minimal oxidation. The substantial TAN reduction after treatment indicates that the oil has undergone partial chemical stability rejuvenation, which makes it ready for demanding lubrication applications.

4.0 Financial Cost Estimation

The economic feasibility of the two-stage recovery process for used SAE 20W40 lubricating oil was evaluated through laboratory-scale cost analysis. The total costs consist of heating and vacuum distillation energy expenses and ZDDP chemical additive costs, filtration material expenses, and operational overhead expenses. The estimated values represent the treatment of one litre of used lubricating oil through batch processing with typical market prices for materials. The analysis evaluates the recovery and treatment expenses to determine if

Table 1. Estimated cost breakdown for the treatment of 1 Litre of used SAE 20W40 lubricating oil

Component	Unit Cost (USD)	Estimated Consumption	Total Cost (USD)
Electricity for Heating (to 240 °C)	0.15 / kWh	2.5 kWh	0.38
Vacuum Pump Operation (1.5 hours)	0.15 / kWh	1.2 kWh	0.18
ZDDP Additive (1 wt.%)	30 / kg	10 g	0.3
Filtration (PTFE membrane, 0.45 µm)	1.50 / membrane	1 membrane per litre	1.5
Glassware/Maintenance (amortised)	—	—	0.1
Labour and Misc. (per litre basis)	—	—	0.2
Total Estimated Cost (per litre)			2.66

they remain below virgin SAE 20W40 oil market prices for both economic and environmental sustainability purposes. The financial cost estimation is presented in Table 1.

The described method costs approximately USD 2.66 to treat one litre of used lubricating oil. The market price of virgin SAE 20W40 lubricating oil exists between USD 3.50-4.50 per litre based on brand and regional factors. The proposed method provides a potential cost reduction of between 25 to 40 % when excluding environmental and waste management advantages. The cost per litre will decrease significantly when the process operates at scale because of bulk purchasing, automated systems, and optimised energy consumption. The two-stage treatment process demonstrates both environmental and performance effectiveness and economic viability for small-to-medium industrial operations and municipal facilities that want to recycle lubricants within their facilities.

5.0 Conclusion

This study proved that vacuum distillation followed by ZDDP chemical treatment successfully recovered and restored the performance of used SAE 20W40 lubricating oil in two stages. The study showed that thermal distillation successfully extracted volatile contaminants and degraded additives and moisture from the oil, while ZDDP replenishment helped restore anti-wear and oxidative stability properties. The treated oil matched virgin SAE 20W40 oil quality in multiple essential parameters through physicochemical analysis, including density, viscosity, viscosity index, flash point, fire point, pour point and TAN. The key findings are as follows:

- Treated oil's density increased from 910 kg/m^3 (untreated) to 884 kg/m^3, closely matching virgin oil, indicating successful volatile removal and base oil retention.
- Viscosity improved from 167 cP (untreated) to 266 cP (treated), indicating restored film strength, though it suggests the need for controlled additive dosing.
- Viscosity Index increased from 51 (untreated) to 81 (treated), demonstrating improved temperature-viscosity stability due to ZDDP's oxidative protection.
- Flash and Fire Points - Treated oil showed elevated flash and fire points relative to virgin oil due to the removal of low-boiling volatiles during distillation.
- Pour Point improved from -12 °C (untreated) to -18 °C (treated), matching virgin oil and ensuring cold-weather operability.
- TAN reduced from >10 mg KOH/g (untreated) to ~2 mg KOH/g (treated), indicating removal of acidic degradation products and effective ZDDP neutralisation.
- Specific Gravity increased from 0.910 to 0.884 after treatment, aligning with standard SAE

20W40 values and indicating recovery of base oil consistency.

- Treatment cost of ~USD 2.66 per litre is 25-40% lower than the market cost of virgin SAE 20W40 oil.
- Environmental Benefit - offers an eco-friendly solution for used oil disposal, reducing pollutant release and supporting circular economy initiatives.

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