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# Removal of Dibenzyl Disulfide (DBDS) by Polyethylene Glycol Sodium and Its Effects on Mineral Insulating Oil

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**ABSTRACT** Dibenzyl disulfide (DBDS) is the major corrosive sulfur compound in mineral insulating oils, which will corrode the copper wires of windings in the oil-immersed power transformers and reactors and eventually cause operation failures. This paper studies the method to eliminate DBDS in insulation oils using the Polyethylene Glycol Sodium (Na-PEG) reagent. The preparation method of the Na-PEG reagent from NaOH and polyethylene glycol 400 is studied in the laboratory. The effect of the Na-PEG reagent dosage and reaction temperature on eliminating DBDS in insulating oils is studied, and a treatment process is recommended. An automatic processing device to remove DBDS from the transformer oil is developed, and the short-term electrical properties and long-term thermal stability of the insulating oil after the Na-PEG reagent treatment are tested. The results show that the Na-PEG reagent can efficiently eliminate DBDS in the insulating oil (the DBDS concentration decreases from 448 mg/kg to less than 5 mg/kg (undetectable) within 1 hour) and will not significantly negatively affect the oil properties such as the breakdown strength at the power frequency, dissipation factor or acidity. A preliminary exploration of the reaction mechanism is explored.

**INDEX TERMS** DBDS, Na-PEG, mineral insulating oil, corrosion prevention, oil regeneration.

## I. INTRODUCTION

Oil-immersed power transformers and reactors are the major equipment in power systems, and severe transformer or reactor failures may cause tremendous economic loss [1]. The oil-paper insulation is a significant component of the insulation system of transformers and reactors, and the degradation of the oil-paper insulation is one of the top causes of equipment failures [2]. Many cases of transformer and reactor failures caused by breakdown in the turn-to-turn insulation have been reported worldwide in the past decade as a result of the winding corrosion caused by corrosive sulfide in the insulating oil [3], [4]. Dibenzyl Disulfide (DBDS), a major corrosive sulfide in mineral insulating oil, reacts with copper wires and produces cuprous sulfide ( $\text{Cu}_2\text{S}$ ) on the surface of copper and insulating paper [5]–[7]. The deposition of  $\text{Cu}_2\text{S}$  on the insulating paper distorts the electric field, weakens the dielectric

strength of the paper, reduces the starting voltage of partial discharge due to the conductivity of  $\text{Cu}_2\text{S}$ , and eventually causes breakdown in the turn-to-turn insulation [8]–[10].

Some methods have been applied to prevent windings from sulfur corrosion. Triazole-based metal passivators such as 1,2,3-benzotriazole (BTA) and Irgamet 39<sup>TM</sup> (CIBA Specialty, Basel, Switzerland) are most commonly used in insulating oils [11]. By forming an impermeable complex layer on the surface of copper, the passivator can delay the reaction between copper and DBDS [12], [13]. However, the complex layer tends to be destroyed at high temperature or under mechanical stress, and the passivator will be consumed as the power equipment runs; thus, it eventually fails to protect the windings [12], [14]. Moreover, the metal-passivation-induced stray gassing effect may affect the dissolved gas analysis of the insulating oil [15].

An alternative method for corrosive protection is to remove the corrosive compound in oil by physical adsorption or chemical reaction. Adsorbents such as molecular sieve, silica

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gel and activated clay yield remarkable effects on the DBDS adsorption in the oil at an oil/adsorbent ratio of 10:1. However, the process usually takes tens of hours, and a relatively high concentration of DBDS remains in the oil [16], [17].

Ag-Y(0.5–1.0 wt%), Ce-Y, and Cu-Y(1.0–3.0 wt%) zeolites show better performance in DBDS adsorption while the preparation of adsorbents is complicated and time-consuming including filtration, cleaning and calcination [18].

An extractive refining treatment with N-Methyl-2-pyrrolidone shows high efficiency in removing the sulfur compound in the oil especially for DBDS, but the extraction process was also complicated performed in three consecutive batch extractions with solvent/oil weight ratios of 0.5/1 in the first stage, 0.4/1 in the second stage, and 0.3/1 in the final stage [19].

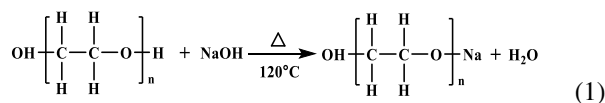
Polyethylene glycol sodium (Na-PEG) is usually applied to remove the toxic polychlorinated biphenyl (PCB) in the transformer oil, and its potential to remove the DBDS in oil was proposed in [20]. However, there is no detailed report about the conditions and efficiency of the reaction between Na-PEG and DBDS and the effect of the Na-PEG treatment on the short and long-term performance of insulating oil.

In this paper, the Na-PEG preparation method was explored, and contrast experiments were performed to determine the suitable dosage of Na-PEG and the proper reaction temperature to remove DBDS in the oil. The short and long-term properties after the accelerated aging experiment of the regenerated oil were studied to estimate the effect of the regeneration method on the oil.

## II. ELIMINATION OF DBDS IN THE OIL BY NA-PEG

### A. PREPARATION OF THE NA-PEG REAGENT

The Na-PEG reagent was prepared with reference to the industrial method of making sodium alkoxide by the reaction between NaOH and the corresponding alcohols. NaOH (Analytical Reagent, AR) and polyethylene glycol (AR) with an average molecular weight of 400 (PEG-400) were used to prepare Na-PEG according to the principle in (1). To determine the proper reaction temperature of the Na-PEG preparation, two factors were considered: First, PEG-400 is stable at room temperature, while at a temperature above 130 °C, it will react with O<sub>2</sub> in the air, and the boiling point of PEG-400 is approximately 250 °C. Second, H<sub>2</sub>O is a reaction product, and the accumulation of H<sub>2</sub>O reduces the reaction efficiency. Therefore, a reaction temperature of 120 °C was selected to avoid the reaction between PEG-400 and O<sub>2</sub>, and H<sub>2</sub>O was evaporated from the beaker to promote the Na-PEG production.



The PEG-400 density is 1.125 g/mL with an average molecular weight of 400, and the NaOH density is 2.13 g/cm<sup>3</sup> with a molecular weight of 39.9. Theoretically, it will take 8.9 mL of PEG-400 per gram of NaOH for an adequate

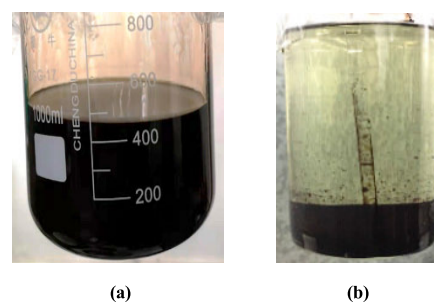


FIGURE 1. Na-PEG reagent and layering of oil and Na-PEG reagent. (a) Na-PEG reagent; (b) Layering of oil and Na-PEG reagent.

reaction. However, the ratio of reagents actually consumed in the reaction must be experimentally determined due to factors such as the test conditions and reagent purity.

PEG-400 is a colorless, odorless and viscous liquid at room temperature. The viscosity of PEG-400 decreases when the temperature increases, but it remains clear. First, 500 mL PEG-400 in a beaker was heated to 120°C; then, NaOH powder was slowly added into PEG-400 while we rapidly stirred using a glass rod. The stirring accelerated the dissolution of NaOH and the evaporation of the generated H<sub>2</sub>O, which would promote the Na-PEG production. During the reaction, the mixture of PEG-400 and NaOH changed from colorless into faint yellow and continued becoming deeper in color. We continued adding NaOH until it no longer dissolved, and we continued stirring until it became dark brown as shown in Fig. 1(a), which implies that the Na-PEG preparation completed. It took 10 mL of PEG-400 per gram of NaOH, which is similar to the theoretical ratio.

The Na-PEG reagent was viscous and insoluble in mineral insulating oil with a larger density than oil (approximately 0.890 g/mL) at room temperature. When it was added into the insulating oil, the Na-PEG reagent sunk to the bottom of the beaker and naturally separated from the oil as shown in Fig. 1(b).

### B. REACTION CONDITIONS OF DBDS REMOVAL BY NA-PEG

Two significant reaction factors should be determined: the dosage of Na-PEG reagent in the treatment and the effect of the reaction temperature and duration on the DBDS removal.

The Na-PEG reagent was prepared by the described method. To obtain the oil sample with a certain DBDS content, DBDS powder was added into the Karamay #25 naphthenic mineral insulating oil, which did not contain any DBDS. Then, the oil solution was stirred by a glass rod and kept in a sealed beaker at 60 °C for 30 minutes for dissolution.

The insulating oils of the transformers and reactors that suffered from failures caused by corrosive sulfur were found to contain 20-200 mg/kg of DBDS [4]. In this part, a batch of oil with a DBDS concentration of 168 mg/kg was prepared for the following experiment to determine the proper reaction conditions. The DBDS concentration in the oil was measured by Agilent 7890A Gas Chromatography instrument and

**TABLE 1. Process of oil treated by different amounts of Na-PEG.**

	Reaction	Layering	Supernatant oil
Oil treated by 10mL Na-PEG			
Oil treated by 20mL Na-PEG			
Oil treated by 40mL Na-PEG			

**TABLE 2. DBDS concentration in oil.**

Na-PEG dosage	DBDS concentration in the oil (mg/kg)		
	0 min	15 min	60 min
10 mL	168	31	13
20 mL	168	<5	<5
40 mL	168	<5	<5

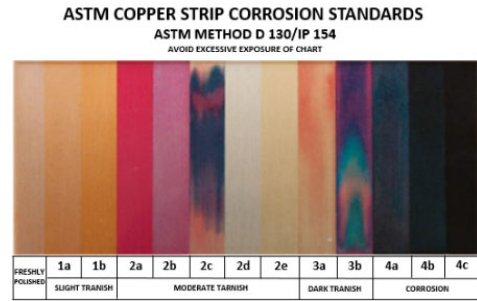
Electron Capture Detector (ECD) according to IEC 62697-1 [22]. Two parallel tests were performed, and the results were averaged.

**1) DOSAGE OF NA-PEG REAGENT IN THE DBDS REMOVAL**

To determine the dosage of Na-PEG reagent for the DBDS elimination, 10 mL, 20 mL and 40 mL of Na-PEG reagent were used to treat the insulating oil with a DBDS concentration of 168 mg/kg at 90 °C with reference to paper [20], and the process is illustrated in Tab. 1. During the treatment, the

**TABLE 3. 72-hour thermal aging test for potentially corrosive sulphide.**

Number	#1	#2	#3	#4	#5
Oil sample description	Fresh oil	Oil with 168 mg/kg DBDS	#2 Oil treated by 10mL Na-PEG	#2 Oil treated by 20mL Na-PEG	#2 Oil treated by 40mL Na-PEG
Insulating oil					
Insulating oil after 72-hour thermal aging test					
Copper wires after 72-hour thermal aging test					



**FIGURE 2. ASTM D130/TP 154 standard colorimetric card.**

supernatant oil was taken for the DBDS concentration test, and the results are listed in Tab. 2.

A 72-hour thermal aging test was performed to identify the corrosiveness of the treated and untreated oil according to IEC 62535-2008 [23]. After the accelerated aging test, the surface of copper wires as shown in Tab. 3 were compared with the ASTM D130/TP 154 standard colorimetric card (Fig. 2) to qualitatively determine the corrosiveness of the oil.

As the result of the 72-hour thermal aging test shows, there was dark tarnish on the surface of copper wire of the oil with 168 mg/kg DBDS, which was close to the corrosion level of 3b in Fig. 2. There was no visible deposition on the surface of copper wires of both fresh oil and treated oil, and the corrosion level was freshly polished. After a 60-minute treatment, the DBDS concentrations of the oil treated by 20 mL and 40 mL Na-PEG reagent were less than 5 mg/kg (undetectable), which implies that DBDS in the oil was eliminated. However, 13 mg/kg DBDS remained in the oil treated by 10 mL Na-PEG, i.e., 10 mL of Na-PEG was insufficient in this treatment. Thus, it was easy to calculate that the exact amount of Na-PEG reagent to react with 500 mL oil with 168 mg/kg DBDS was 10.84 mL, i.e., approximately 1 mL Na-PEG: 7 mg DBDS.

**TABLE 4. DBDS concentration in oil at different temperatures over time.**

Reaction temperature	DBDS concentration in the oil (mg/kg)			
	0 min	5 min	15 min	60 min
70 °C	168	32	12	< 5
80 °C	168	30	6	< 5
90 °C	168	21	< 5	< 5
100 °C	168	14	< 5	< 5

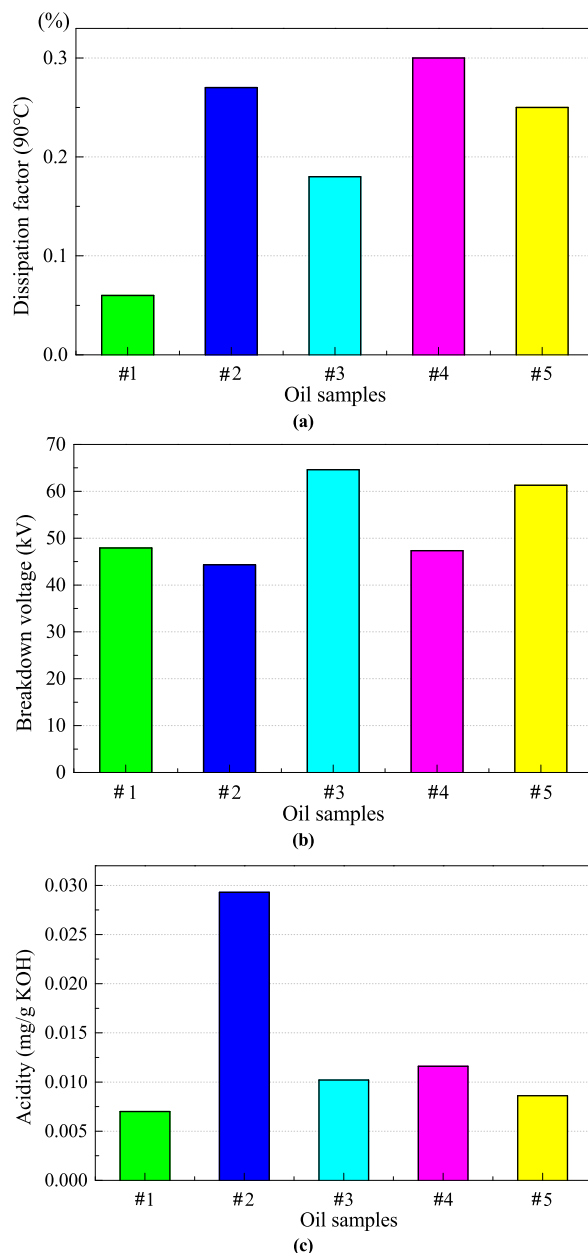
**2) EFFECT OF THE REACTION TEMPERATURE AND DURATION ON THE DBDS REMOVAL**

In addition to the dosage of Na-PEG reagent, a proper reaction temperature was determined. The actual operating temperature of transformer oil is commonly 70-90 °C. Thus, a comparative experiment was performed to treat the oil with 168 mg/kg DBDS at 70 °C, 80 °C, 90 °C and 100 °C. As the result shows in Tab. 4, DBDS in the oil sharply decreased from 168 mg/kg to 14-32 mg/kg within 5 minutes of reaction. At a higher temperature, less DBDS remained in the oil, i.e., the corresponding reaction rate was faster. After 15 minutes of reaction, the DBDS concentrations in the oil at 90 °C and 100 °C were less than 5 mg/kg (undetectable), while those at 70 °C and 80 °C were less than 18 mg/kg. After 60 minutes, all DBDS concentrations were less than 5 mg/kg (undetectable), which indicates that DBDS was eliminated. Based on this experiment, the temperatures of 70-100 °C share a similar effect on the reaction rate when the treatment time is 60 minutes. A reaction temperature of 75±2 °C and a duration of 60 minutes were selected for the following treatment.

In this part, some experiment parameters were determined: The reaction temperature of the Na-PEG preparation was 120 °C, and the ratio of reactants was 1 g NaOH: 10 mL PEG-400. The reaction temperature of Na-PEG and DBDS was 75±2 °C. The ratio of reactants was 1 mL Na-PEG: 7 mg DBDS, and the treatment duration was 60 minutes.

**3) DIELECTRIC PROPERTY OF OIL TREATED BY NA-PEG IN THE BEAKER EXPERIMENT**

To initially assess the effect of Na-PEG on the dielectric property of oil, five oil samples were prepared for a comparison test: fresh oil (#1), oil with 168 mg/kg DBDS (#2) and oil with 168 mg/kg DBDS treated by 11 mL (complete reaction), 20 mL and 40 mL Na-PEG (#3, #4 and #5) in the beaker condition. DBDS and Na-PEG were supposed to fully react in oil #3, while the Na-PEG reagent in oil #4 and oil #5 were excessive. To eliminate the effect of the ambience, all samples were dehydrated and degassed in a vacuum oven at 90 °C/50 Pa for 24 hours. Then, the basic dielectric properties of oil including the dissipation factor, breakdown voltage at power frequency and acidity were tested. The breakdown voltage at power frequency is tested by IJJD-80 Insulating Oil Dielectric Strength tester according to IEC 156 [24]. The dissipation factor of oil was tested by the JKJD200-1 Dissipation Factor and Resistivity tester according to



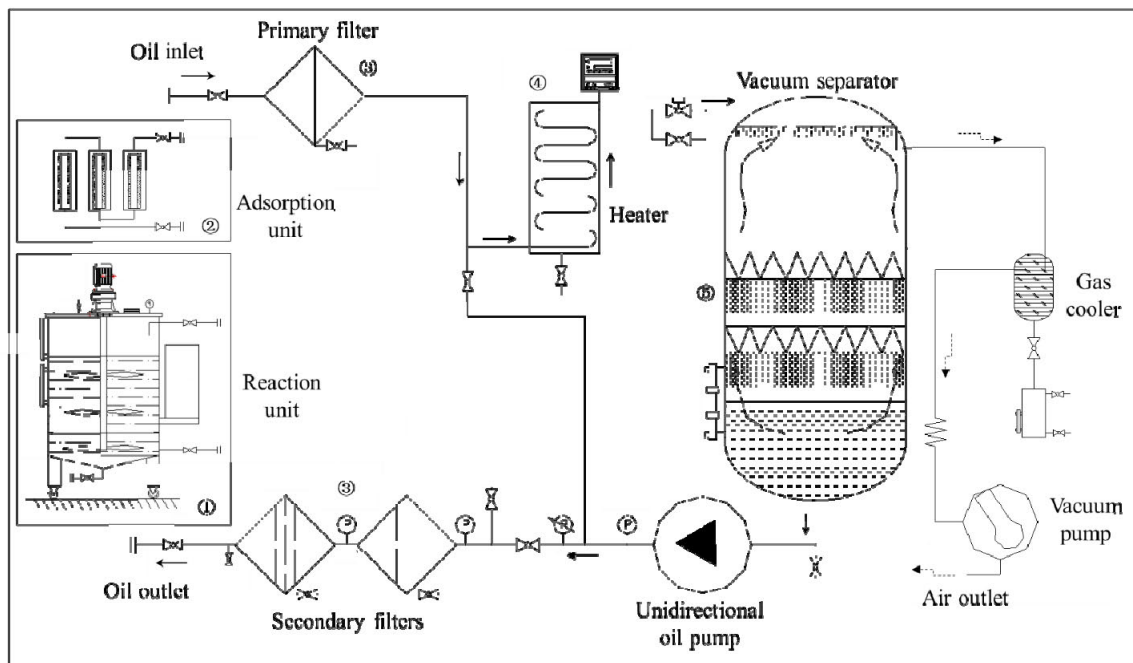
**FIGURE 3. Properties of oil in the beaker experiment. (a) Dissipation factor of oil (b) Breakdown voltage of oil at the power frequency. (c) Acidity of oil.**

IEC 60247 [25]. Two parallel tests were performed, and the results were averaged. The acidity of oil was measured by Metrohm 907 Titrando according to IEC 62021-1 [26]. The results are shown in Fig. 3.

Some evidences can be drawn from the test results. Generally, the treated oil has better dielectric properties than that with 168 mg/kg DBDS. Thus, the Na-PEG treatment will not introduce a significant adverse effect on the basic dielectric performance of oil. Among the three treated oils, oil #3 shows a better performance than oil #4 and oil #5, especially for the dissipation factor and breakdown voltage. Based on this result, the Na-PEG dosage should be controlled to ensure an adequate reaction and avoid excessive use. Although an



(a)



(b)

**FIGURE 4.** Oil-regenerating device. (a) Physical picture of the oil-regenerating device. (b) Schematic diagram of the oil-regenerating device.

improvement was observed, the parameters of the treated oil, especially the dissipation factor, were not as good as those of fresh oil. More work was performed to improve the regenerating process to narrow the quality gap between treated oil and fresh oil.

### III. DEVELOPMENT OF THE AUTOMATIC PROCESSING DEVICE OF DBDS REMOVAL AND ITS EFFECT

All of the above experiments were performed in small doses in beakers. In the treatment process of layering in Tab. 1, some small particles produced during the reaction inevitably resided in the supernatant oil, and trace amounts of air and moisture dissolved in the oil, which negatively affect the dielectric properties of the insulating oil. Thus, an automatic oil process device was developed to improve the DBDS removal efficiency and the quality of the treated oil.

#### A. STRUCTURE OF THE OIL REGENERATION DEVICE

The oil regeneration device consisted of three parts: chemical reaction unit, physical adsorption unit and vacuum separation unit, as shown in Fig. 4.

In the treatment process, first, the insulating oil with DBDS reacted with the Na-PEG reagent in the reaction unit ①; then, the oil was kept stable for layering. Next, the supernatant clear oil went through the adsorption unit ②, which was driven by a unidirectional oil pump. The adsorption unit consisted of three serial filter cartridges with silica gel and activated clay in them, which adsorbed small particulate impurities in the oil and purified the oil due to their loose and porous structures. Immediately after the adsorption, the insulating oil went through the vacuum separation unit, which consisted of a primary filter and a secondary filter ③, a controllable heater ④ and a vacuum separator ⑤. In this unit, the oil was heated to  $75 \pm 2^\circ\text{C}$  by a controllable heater and flowed into the vacuum

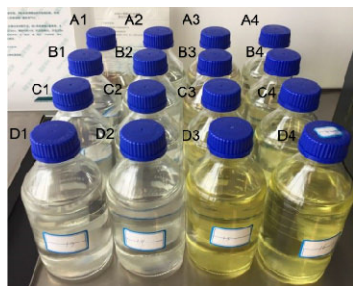


FIGURE 5. Each stage of four sample groups.

separator for degassing and dehydrating, by which the moisture and dissolved gas in the oil were reduced to a relatively low level. The primary and secondary filters filtered the small particles in the oil. The entire treatment could be repeated several times to achieve a satisfactory oil regenerating result.

### B. SHORT-TERM PROPERTIES OF THE OIL AFTER REGENERATION

A comparative experiment was performed for the oils with 37 mg/kg (group A), 73 mg/kg (group B), 139 mg/kg (group C) and 448 mg/kg (group D) DBDS to be treated by the regeneration device. The procedure of the experiment is listed in Tab. 5. Oil samples were taken at every stage as shown in Fig. 5 for the tests, including the DBDS concentration, corrosiveness, breakdown voltage at power frequency, dissipation factor and moisture content of the oil. The moisture content in the oil was tested by the JF-5 Coulomb Micro-water tester according to ASTM D1533-12 [27]. Two parallel tests were performed, and the results were averaged only if the difference between two results was within 2 mg/kg.

### C. LONG-TERM THERMAL STABILITY OF THE REGENERATED OIL

The dielectric properties of the newly regenerated oil were tested in the previous experiment, and another experiment was performed to explore the long-term stability of the regenerated oil after 30 days of thermal aging at 120 °C. The oil with 172 mg/kg of DBDS was treated by the regeneration device and set as group I. The oil with 172 mg/kg of DBDS (group II) and fresh oil without DBDS (group III) were the controlled groups.

The accelerated thermal aging experiment was conducted as follows: First, the experimental materials were pretreated. Kraft insulating paper, 70 mm×10 mm×2 mm windings samples with 2 layers of paper and three batches of insulating oil were dehydrated and degassed in a vacuum oven at 90 °C/50 Pa for 24 hours. Then, the paper and windings were immersed in oil at a ratio of 0.05 g (paper): 0.05 cm<sup>2</sup> (winding): 1 g(oil) at 60 °C/50 Pa for another 48 hours. Afterwards, every group of samples was put into a sealed stainless-steel can, and the can was filled with nitrogen to exhaust air as shown in Fig. 6. Finally, three cans were put into a thermal tank at 120 °C for a 30-day aging experiment.

TABLE 5. Experiment procedure of oil regeneration.

Experiment stage	Operation description
Stage 1	Fresh oil
Stage 2	Put the fresh oil with a certain content of DBDS into the reacting tank
Stage 3	Add a suitable amount of Na-PEG reagent into the reacting tank and continue stirring for 1 hour at 75±2 °C, then 8 hours of standing and layering
Stage 4	Dehydrate and degas the supernatant oil for 4 hours

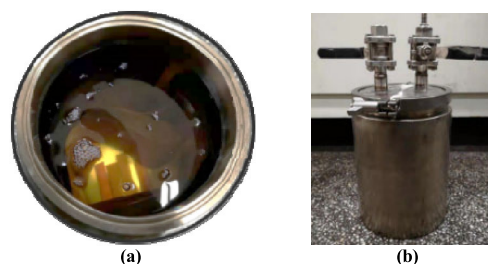


FIGURE 6. Samples in the stainless-steel can for the thermal-aging experiment. (a) Oil-immersed windings and paper. (b) Stainless-steel can.

After the thermal aging experiment, the samples were taken from the stainless cans for direct testing. For the oil, the DBDS concentration, dissipation factor, breakdown voltage at power frequency, acidity and moisture content were measured and analyzed. For the paper and winding, a SEM/EDS test was performed to observe the microscopic morphology and analyze the element distribution on the surface of the paper and copper wires by a JEOL JSM-7800F Field Emission Scanning Electron Microscope. The test results are listed in Tab. 6 and Tab. 7.

## IV. RESULTS AND DISCUSSION


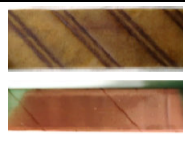
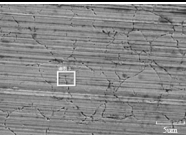
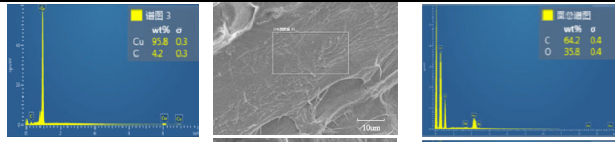


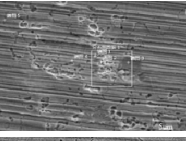
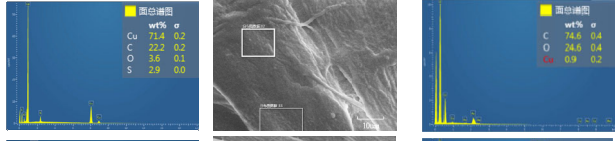



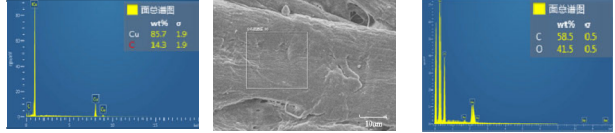
### A. PROPERTIES OF THE OIL AFTER REGENERATION

As shown in Fig. 7(a), the oils with the original DBDS concentration from 37 mg/kg to 448 mg/kg witnessed a sharp drop to less than 5 mg/kg (undetectable) after the treatment by the Na-PEG reagent (as shown in stage 2 and 3), which confirms the efficiency of the DBDS removal by Na-PEG.

A decrease in breakdown voltage of 5-8 kV was observed from stage 2 to stage 3 in Fig. 7(b), which implies that the reaction process may introduce a slight negative effect on the dielectric strength of the oil. However, after the follow-up treatment by adsorption and vacuum separation, the breakdown voltage increased to a level near that of fresh oil. Considering the moisture content trend in the oil in Fig. 7(d), the treatment process might have caused an increase in amount of dissolved water in the oil, which decreased the breakdown voltage.

There may be two sources of increased moisture content in the oil: the contact between oil and ambient air, which

**TABLE 6. Morphology and SEM/EDS results of the samples after the accelerated thermal-aging experiment.**

	Oil	Winding	SEM/EDS of copper surface	SEM/EDS of inner surface of paper
Regenerated oil (group I)				
Oil with 172mg/kg DBDS (group II)				
Fresh oil (group III)				

**TABLE 7. Properties of oil after 30 days of aging at 120 °C.**

	Regenerated oil (group I)	Fresh oil (group II)	Oil with 172mg/kg DBDS (group III)
Breakdown voltage (kV)	54.8	58.9	55.8
Moisture (mg/L)	14.5	16.6	17.2
Tan δ (%)	0.188	0.149	0.150
Resistivity (e11Ωm)	7.28	10.02	9.08
Acidity (mg/g (KOH) )	0.0070	0.0056	0.0062

contains vapor, and the possible production of H<sub>2</sub>O in the reaction between Na-PEG and DBDS.

As shown in Fig. 7(c), the dielectric losses of the treated oils were generally smaller than those of the untreated oil, which implies that the regenerating process reduces the dissipation factors of the oil due to the adsorption and vacuum separation treatment.

**B. LONG-TERM STABILITY OF THE TREATED OIL AFTER THERMAL AGING**

The long-term stability of the treated oil after thermal aging was characterized by both oil and windings. The microscopic morphology and element distribution of the surface of the paper and copper wires reflect the corrosiveness of the oil, and the dielectric parameters of the oil help to evaluate whether the reaction affects the dielectric property of the oil under long-term operation conditions.

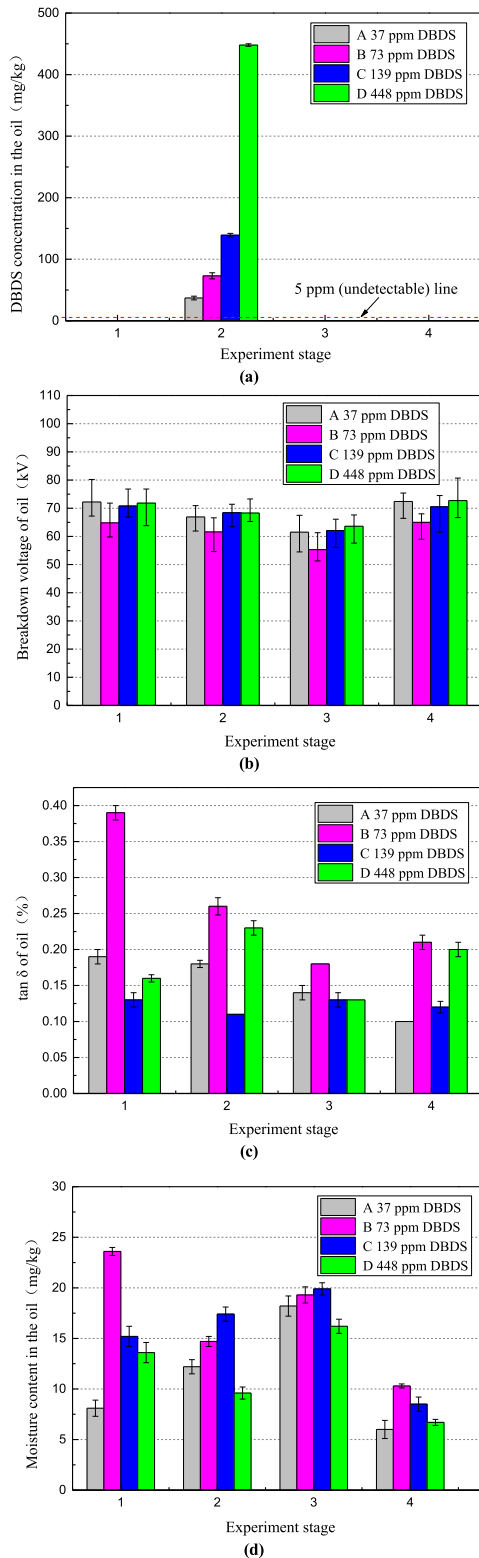
Images of the oil and windings after the accelerated thermal-aging experiment and the SEM/EDS test results are listed in Tab. 6. Three groups of oil were clear except for the difference in color depth. The oil of group II was lighter in color than the fresh oil because DBDS is an excellent antioxidant [21] and slows down its degradation. The oil of

group I was darker in color than the fresh oil as a result of the effect of Na-PEG as shown in Fig. 1(a).

For the windings, there was a significant discoloration on the surface of the copper wires of group II, which indicates a serious corrosion degree of 4a-4b (referring to the ASTM D130/TP 154 standard colorimetric card). The SEM/EDS results also show numerous corrosion pits on the surface of the copper wires of group II, and the content of S element in these areas was approximately 2.9wt% (weight percent), which indicates that the sulfur corrosion occurred. The surface of the cellulose of group II was smooth without visible particle deposition, and 0.9wt% of Cu element was detected, which may originate from the dissolved Cu<sup>2+</sup> or Cu<sup>1+</sup> in the oil. No S element was detected on the surface of the paper because the sulfur deposition on copper wires had not migrated to the paper yet.

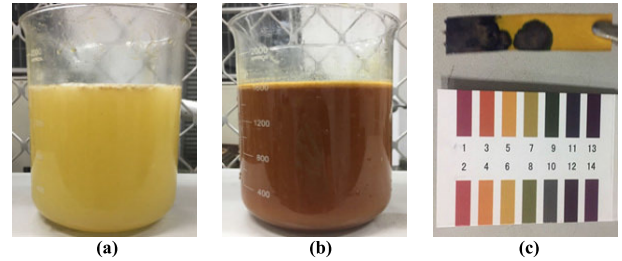
No obvious discoloration or corrosion pits were observed on the copper surface of group I and group III, and no other elements were detected except Cu and C (Group I: Cu 95.8wt%, C 4.2wt%; Group III: Cu 85.7wt%, C 14.3wt%), the surface of the corresponding cellulose of papers was smooth without visible particle deposition, and no other element was detected except C and O (Group I: C 64.2wt%, O 35.8wt%; Group III: C 58.5wt%, O 41.5wt%). The SEM/EDS result shows that neither oil of group I nor group III was corrosive.

The properties of oil after the aging experiment are listed in Tab. 7. The difference between the moisture of three oil samples was within 3 mg/kg, which were at the same level. The breakdown voltages at the power frequency of oil I and III were 3.1-4.1 kV (5.3-6.9%) lower than that of fresh oil. The dissipation factor of oil III was 0.150 %, almost identical to fresh oil, which indicated that 172 mg/kg DBDS has no obvious effect on the dielectric loss of oil under the condition of the 30-day thermal aging. The dissipation factor of oil I increases to 0.188 %, which implies that the reaction residues negatively affect the dielectric loss of oil even through adsorption and vacuum separation, so there is still



**FIGURE 7. Dielectric properties of the oil. (a) DBDS concentration in the oil. (b) Breakdown voltage at the power frequency of the oil. (c) Dissipation factor of the oil. (d) Moisture content in the oil.**

space for improvement in the regeneration process. However, Tan  $\delta$  of 0.188 % was much lower than 0.5% in IEC 60296-2012 [28]. There was no significant difference in acidity or

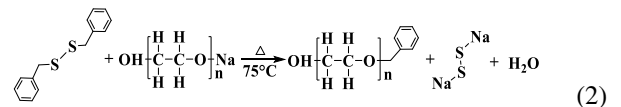


**FIGURE 8. Properties of the post-reaction deposit water solution. (a) Low concentration (b) High concentration (c) PH value.**

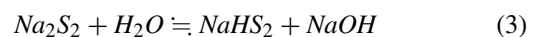
resistivity among the three oil samples. Hence, the DBDS elimination by the Na-PEG reagent will not accelerate the degradation of the insulating paper.

**C. DISCUSSION ON THE REACTION PRINCIPLE BETWEEN DBDS AND NA-PEG**

The reaction principle of the DBDS elimination is speculated as in (2) based on the above experiment results. As one of the resultants, H<sub>2</sub>O explains the increase in moisture content in oil from stage 2 to stage 3 in Fig. 7(d).



During the experiment, some properties of the post-reaction deposit are similar to sodium persulfide (Na<sub>2</sub>S<sub>2</sub>). Na<sub>2</sub>S<sub>2</sub> dissolves in water and alcohols, and the color of its low-concentration solution is yellow, while high concentrations become reddish brown. The solutions of the post-reaction deposit in Figs. 8(a) and (b) have the same colors as Na<sub>2</sub>S<sub>2</sub>. Na<sub>2</sub>S<sub>2</sub> also undergoes a hydrolysis as in (3), which produces an alkaline solution and a hepatic gas (H<sub>2</sub>S).



When the post-reaction deposit dissolved in water, it smelled like H<sub>2</sub>S, and the PH value of the water solution was approximately 11 as shown in Fig. 8(c), which supports the reaction of (2) and (3). However, the specific reaction principle remains unclear. In the subsequent study, appropriate detection methods and instruments remain necessary to accurately characterize the reactants and products to clarify the reaction mechanism. The clarification of the reaction mechanism will help to clarify the potential impact of the DBDS elimination reaction on the dielectric properties of the insulating oil, improve the sulfur removal process and find alternative reagents with similar effects but less influence on the performance of the insulating oil.

**V. CONCLUSION**

(1) The effect of DBDS removal in insulating oil by the Na-PEG reagent was investigated. By adding Na-PEG to the corrosive oil, the DBDS concentration decreased from 168 mg/kg to 12-30 mg/kg within 5 minutes and finally less than 5 mg/kg in 60 minutes. A ratio of 1 mL Na-PEG to 7 mg



DBDS in oil and a reaction temperature of  $75 \pm 2$  °C were recommended according to the experimental results in this work.

(2) An automatic processing device to remove DBDS in the transformer oil was developed. The DBDS concentration in the oil decreased from 448 mg/kg to less than 5 mg/kg within 60 minutes, and the oil became non-corrosive. The thermal aging experiment result shows that the regeneration efficiently removes DBDS in the oil but does not introduce any significant adverse effect on the oil properties such as breakdown voltage at the power frequency, dissipation factors or acidity.

(3) A preliminary analysis of the reaction mechanism between DBDS and Na-PEG was conducted. Although the specific reaction principle remains unclear, the study has laid a foundation for subsequent research and the improvement of oil regeneration.

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