Performance Analysis of Cellulose and Nomex-910 Impregnated Oil Filled Power Transformers

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Abstract: In the present paper, the influence of accelerated thermal aging on thermally upgraded Kraft and Nomex 910 insulated power transformers has been determined. The present experimental study also determines the effectiveness of 2, 6-dibutyl-4-methylphenol oxidative inhibitor on the degradation rate of mineral transformer oil with alternative solid dielectrics. From the accelerated aging studies, it has been revealed that Nomex impregnated oil samples have shown around 15% improved thermal characteristics over thermally upgraded Kraft oil samples. Also these samples have exhibited 20% enhanced oxidation stability even at temperatures more than 200^{0}C. Therefore, Nomex insulating materials have been recommended as solid dielectrics for power transformers in order to achieve better operating characteristics and improved oxidation stability.
Key words: transformer, insulation, diagnosis, temperature, aging, performance, Nomex

1. Introduction

Power transformers are the most significant devices in substations, and play an important role in electricity transmission. Abnormalities if present in transformers accelerate their aging process. It may finally lead to failure of transformers resulting in a big revenue loss not only to utilities but also to customers [1, 2]. Therefore, the health assessment of transformers has gained an immense importance in recent years [3]. Health status of power transformers is largely depends on the health of their solid insulation. Improved thermal characteristics of solid insulation extend the service life of the transformers. During the past few years, several electrical insulating materials have been developed from different aging models. The operating characteristics of the solid and liquid dielectrics of transformers are largely influenced by electrical and thermal stresses [1]. These stresses inside the transformers accelerate aging, and reduce the operating performance of the insulations. At high temperatures, oxidation rate of transformers insulation is extensively higher [2]. As a result, many undesirable contaminants including solid particles, water content and soluble solar compounds are accumulated within the transformer oil. These particles rapidly change the electrical and the thermal properties of the transformers, and finally lead to insulation failure [3]. During the past several years, a number of researchers have been investigated the influence of thermal aging on the performance of the transformers [3-6]. These studies determine that the aging characteristics of the insulations are satisfactory for new materials but decline with time and temperatures. Thus, the insulating materials having higher operating temperatures should have longer service life time with better thermal characteristics [5, 7].

For the last ten decades, cellulose based Kraft insulating papers have been generally used in oil filled power and distribution transformers [8]. Though the degradation rate of Kraft paper is high, however, it has been preferable by the utilities and consumers because of its low cost and reasonably good performance [5, 8]. In 1950's, thermally upgraded Kraft (TUK) which is an updated version of Kraft was introduced [2]. The development process of TUK chemically treated the paper with a nitrogen based compound such as dicyandiamide [8, 9]. Such chemical treatments stabilize the cellulose molecule hydroxyl radicals. As a result the tendency of insulating paper towards hydrolysis has been achieved. Also, the thermal up-gradation process was widened the operating temperatures of the paper from 95^{0}C to 110^{0}C, suggested by IEEE C57.91 [10]. Similarly, further improvements in operating temperatures of transformer insulating paper have been achieved by using synthetic materials [11, 12]. These synthetic papers

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and films can operate even at higher temperatures (> 220^{0}C and higher) [11]. During the past few years, Dupont has been introducing several electrical insulating papers. Within the Nomex family of products, primarily Nomex 910 and Nomex 410 papers are the high quality insulating materials to address virtually any electrical insulation requirement. Nomex 910 has a unique three-ply construction [12, 13]. The two plies on the outside of the sheet are a combination of cellulose and synthetic aramid. The center ply is composed of cellulose, providing bulk and mechanical support, but with reduced cost. The synthetic aramid ingredient in the outside layer is a fibrid, which is a non granular, fibrous, or film-like particle [7, 13]. The integral and inherent part of this high temperature fibrid gives thermal resistance in the outside layer to the hot active part of a transformer and also contributes excellent electrical properties [14, 15].

Though Nomex insulating papers have improved thermal characteristics over TUK, however, a very little work has been done on these materials [7, 11, 16]. A number of researchers have investigated the influence of thermal aging on the operating performance of the transformers [7-10]. In Ref. [16], Verma fabricated a test cell to carry out the accelerated aging study of oil-immersed transformer. The individual effects of thermal and electrical stresses on transformer insulation were studied. In 2010, Singh designed a test cell for accessing accelerated thermal and electrical aging of the transformer oil and paper insulations [17]. The variations in dielectric properties of Kraft impregnated mineral transformer oil were determined as per the aging. In 2015, Mehta proposed a dual cell that determined the dielectric characteristics of crepe and Kraft papers [18]. However, the above discussed aging models established that the dielectric characteristics are satisfactory for new materials, and decline with time and temperature variations. Thus, the insulating materials having higher operating temperatures need to have longer service life time with better thermal characteristics [11, 12]. However, there is still a need to do much detailed thermal and electro-thermal aging studies of the new solid dielectric materials. This has prompted the authors to study the adaptability of these dielectrics in the power transformers and to finally bring down a comparison of these new dielectrics with thermally upgraded Kraft paper. For this investigation, accelerated aging tests on these insulating materials have been conducted in the laboratory. This is due to the reason that such accelerated aging tests detail the withstanding capability and thermal performance of the insulations even at higher stresses [19].

On the other hand, as it is stated in [20] that transformer oil is a mixture of paraffinic, naphthenic and aromatic hydrocarbons is prone to oxidation. Many polar compounds such as acids, aldehydes, ketones, peroxides and alcohols are formed due to the oxidation of oil. These products affect the insulating properties of oil and heat transfer properties of oil by forming sludge type compound. This reduces the performance of power transformers, thereby reducing their life. In order to improve the stability of mineral transformer oil against oxidation and thereby to improve the life of oil, an additive known as antioxidants or inhibitors are added. Conventionally 2, 6–di-tertiary-butyl-para-cresol (DBPC) is used as the antioxidant. Therefore, accelerated aging tests on DBPC inhibited mineral oil samples with different solid dielectrics have been conducted in the present experimental study.

2. Experimental Work

A. Samples Preparation

A large number of samples were prepared in the present work to carry out the accelerated aging tests. To prepare the test samples for conducting accelerating aging tests, the conical flasks were initially cleaned with purified water, and then dried out in an air-circulated temperature oven (set at 100^{0}C for 24 hours). This is done to remove all traces of humidity from the flasks. The cleaned and dried conical flasks were cooled down to room temperature, and then filled individually with uninhibited fresh mineral transformer oil. Similarly, another set of conical flasks were filled with 2, 6–di-tertiary-butyl-para-cresol (DBPC) oils. The mass ratio of the oil to paper insulations was considered in accordance to IEEE C57.154-2012 [10]. Further, oil filled and unsealed conical flasks were placed in the temperature oven, and subjected to a temperature of 100^{0}C for 24 hours. It is done to ensure the removal of the moisture content which may get added during the preparation of the test samples. Further, different oil samples were separately filled with TUK, and Nomex 910 solid dielectrics, respectively. Also copper in a standard mass ratio was added in the samples. Detailed specifications of the materials used in the samples are as given in Table 1.

Table 1. Detail specifications of the materials.

Material/Item	Specification
Liquid dielectrics	Mineral oil
Solid dielectrics	Thermally upgraded Kraft (TUK) – 3mill, Nomex 910 – 3mill
Copper strip	100mm (length) × 25mm (width) × 3mm (thickness)
Conical flasks	1200ml capacity
Cork	Rubber
Inhibitors	DBPC (6.66 g)

Further the test samples were tightly sealed with cork plugs surrounded with aluminum foil and Kaptan tape to avoid ingress of any outside contaminants. Different materials used in the preparation of the samples, and the temperature oven for conducting the accelerated aging tests are shown in Figure. 1 (a)-(d) and Figure. 1(e) respectively.

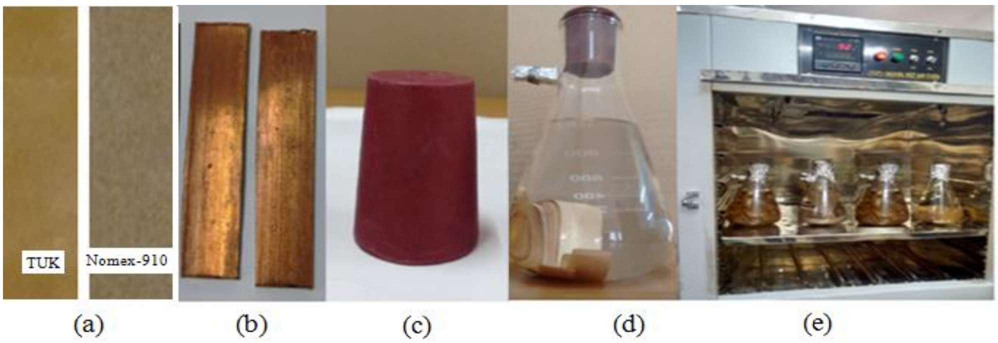


Figure 1. (a) TUK and Nomex 910 solid dielectrics (b) Copper Strips (c) Rubber cork (d) Sample in conical flask (e) Air-circulated PID controlled temperature oven.

B. Accelerated Aging

After the preparation of the test samples, accelerated aging tests were conducted at different temperatures ranging from 100^0C to 220^0C. It is observed during experimental work and several tests that initially for low aging time (i.e. <72 hours) and temperatures up to 160^0C there is a reduction in water content present within transformer oil. This is due to the hydrolysis reaction as well as the absorption of water by the cellulose [5, 19, 21]. Consequently, breakdown voltage (BDV) and interfacial tension (IFT) of transformer oil increase [21]. However, at higher temperatures and aging time ≥72 hours, moisture present in the cellulose and that absorbed by the paper at lower temperatures together migrate into the oil [19, 21], thus changing the oil properties. Therefore, it was decided to age all the test samples for ≥72 hours in order to obtain the significant and realistic changes in the dielectric properties of the transformer oil, for all test temperatures in accordance with Refs. [5, 21]. To carry out the accelerated aging, the samples having different solid and liquid dielectrics were thermally stressed at 100^0C for 72 hours initially, and then cooled down to room temperature. Further each of these oil samples was stored in a dark room and handled in accordance with ASTM D 923 [22]. Subsequently, similar sets of samples were prepared using the same experimental procedure, and subjected to 120^0C for 72 hours duration. Likewise, the other sets of samples were aged at 140^0C, 160^0C, 180^0C, 200^0C and 220^0C temperatures respectively. Thereafter, different tests of transformers insulation were performed on each of the stored test samples. The significances of each of these tests have been detailed in experimental results and discussion section of the paper.

3. Results and Discussion

Various diagnostic parameters namely BDV, IFT and water content (WC) were determined for each of the aged oil samples. For an easy interpretation of the test results, the percentage decrements in BDV and IFT as per the accelerated aging were computed at every test temperature, using (1).

$$Percentage\ decrement\ = \frac{Reference\ value - Measured\ value}{Reference\ value} \times 100 \tag{1}$$

Reference value is the value of the parameter after 100^0C aging. Similarly, the percentage increment in water content as per the accelerated aging was determined using (2).

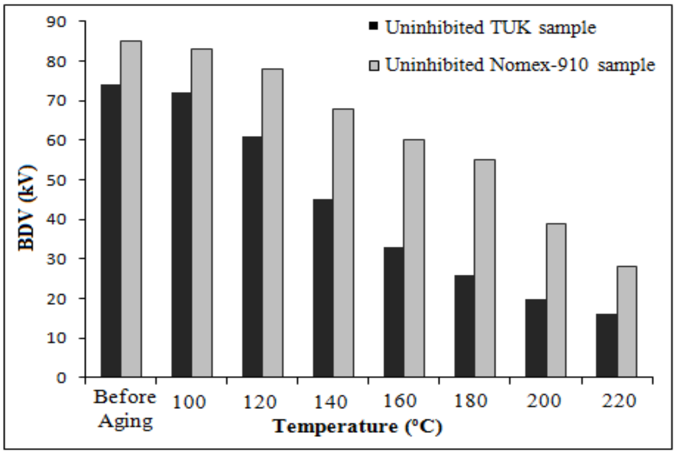
$$Percentage\ increment\ = \frac{Measured\ value - Reference\ value}{Measured\ value} \times 100 \tag{2}$$

The implications of each of these tests are discussed in the subsequent sub-sections.

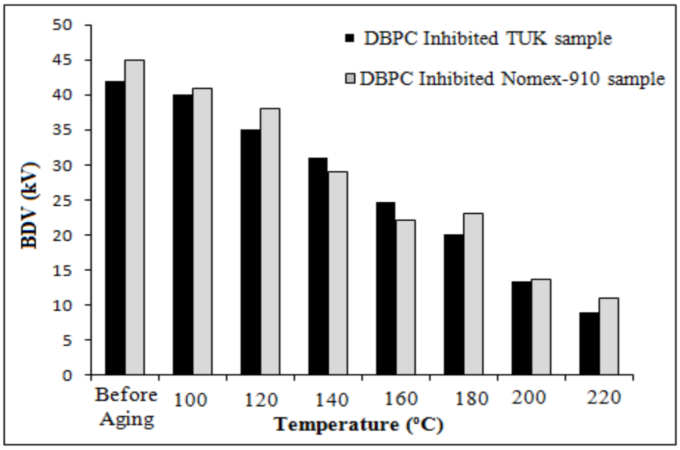
A. Breakdown Voltage

Breakdown voltage test is one of the prominent diagnostic tests of transformers. The maximum voltage that can be applied across the oil without any electrical breakdown is called as breakdown voltage of oil [23]. Any significant reduction in BDV indicates the presence of oil degradation products, cellulose breakdown products, and water content [24]. The test has been performed in accordance to ASTM D 877 [24]. The experimental BDV test set up is shown in Figure. 2. Figure. 3 (a) and (b) details the variations in BDV of uninhibited and DBPC inhibited mineral oil samples, respectively. Similarly, the percentage variations in BDV as per the accelerated thermal aging are shown in Figure. 4. These percentage decrements in BDV are determined by using (1).

Figure 2. BDV test set up installed at TIFAC-CORE centre, NIT Hamirpur.



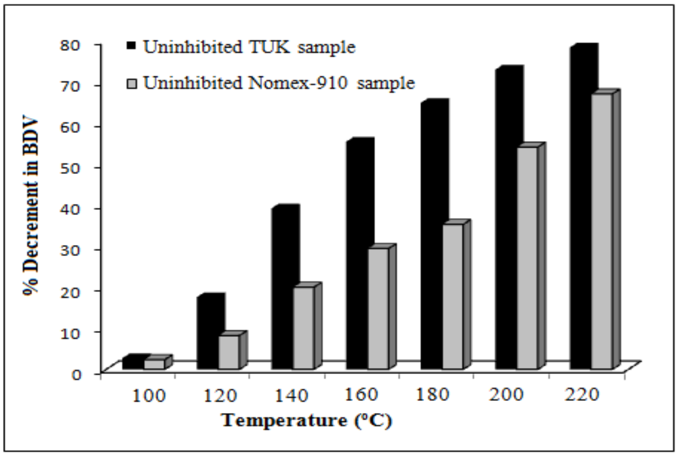
(a)



(b)

Figure 3. Comparison of the change in BDV of (a) uninhibited and (b) DBPC inhibited mineral oil samples over accelerated temperatures.

It has been observed from the test results shown in Figure. 3 that BDV of TUK oil samples falls down by more than 50% when the temperature ranges from 100^0C to 160^0C, calculated using (1). This decrement in BDV from its value at 100^0C is more than 75% at 220^0C. Consequently, BDV of test samples having Nomex 910 decreases to 35% at 180^0C, and nearly 65% at 220^0C. It is clearly determined here that the decrements in dielectric strengths of Nomex impregnated oil samples are lesser than that of TUK based test samples. More specifically, Nomex 910 test samples exhibited 15% improved dielectric strength at 220^0C over TUK oil samples. Synthetic aramids present in Nomex 910 dielectric increased the overall dielectric strength of the test samples.



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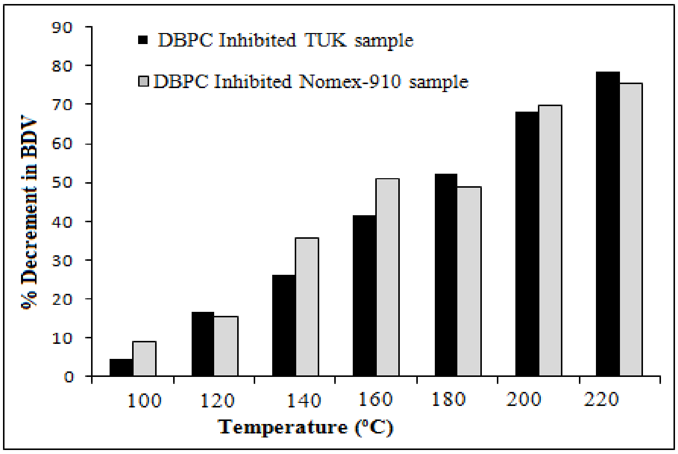


(b)

Figure 4. Percentage decrements in BDV of (a) uninhibited and (b) DBPC inhibited mineral oil samples over accelerated temperatures.

In case of DBPC inhibited oil samples, further improvements in BDV of different test samples were obtained, and are as depicted in Figure. 3 (b) and Figure. 4(b). It is concluded here that the deterioration in BDV of uninhibited oil sample is more as compared to that of inhibited oil sample. This is due to the increased water content and impurities as per accelerated temperatures. The water content within the transformer oil propagates the creation of gaseous substances, and the presence of impurities sharply breaks these gaseous substances. This process is continued till the breakdown of the oil takes place. Thus the presence of inhibitors inside the mineral oil improves its dielectric strength thereby extending the service life of transformers. Therefore, the mineral oil with Nomex-910 has an extended service life time than the service life of the TUK impregnated mineral oil samples.

B. Interfacial Tension

The second diagnostic test which was performed on the aged test samples is interfacial tension. This test determines the presence of polar contaminants and oil decay products [25]. These contaminants extensively decrease the thermal performance of the transformer oil [26, 27]. In general, inter facial tension of new mineral oil without aging is high and it decreases as per aging as well as electrical and thermal stresses. This test was performed in accordance to the instructions of ASTM D 971 [25]. Figure. 5 shows the experimental set up of IFT test, whereas, Figure. 6 (a) and (b) shows the variations in interfacial tensions of different test samples aged at various temperatures. The percentage decrements in IFT of inhibited and uninhibited oil samples are shown in Figure. 7 (a) and (b).

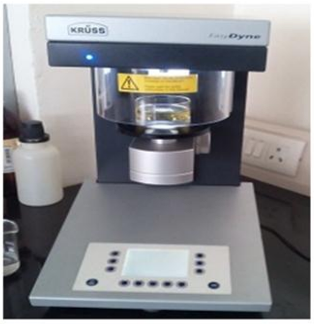
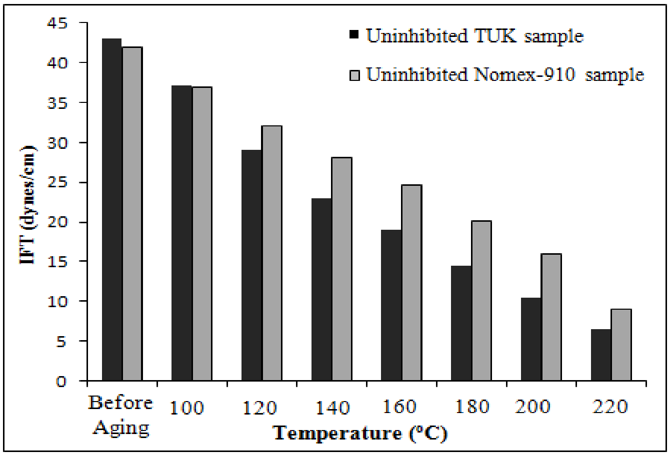
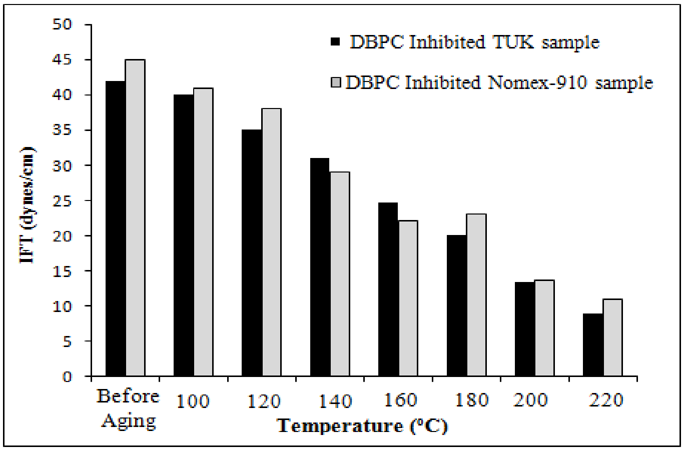


Figure 5. IFT test set up installed at TIFAC-CORE centre, NIT Hamirpur.



(a)



(b)

Figure 6. Comparison of the change in IFT of (a) uninhibited and (b) DBPC inhibited mineral oil samples.

At 180^{0}C, IFT of TUK oil samples falls down to 64% from its value which is obtained at 100^{0}C. Whereas, IFT of Nomex-910 reduces to 53% as compared to the value obtained at 100^{0}C. Similarly, at 220^{0}C, IFT falls down from its rated value by nearly 85% for TUK oil sample and 79% in case of Nomex-910 samples. These significant decrements in IFT of all test samples indicate the presence of larger oxidation contaminants in the samples.

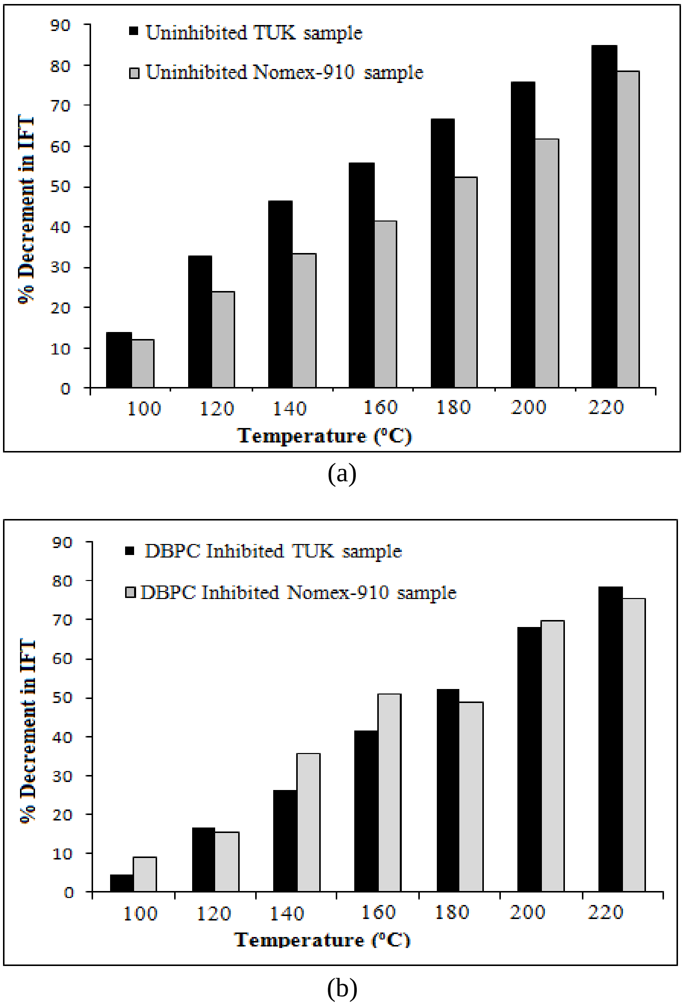


Figure 7. Percentage decrements in IFT of (a) uninhibited and (b) DBPC inhibited mineral oil samples over accelerated temperatures

When a comparison is done amongst the TUK test samples, it is found that these samples have higher oxidation contaminants than the Nomex-910 oil samples. Consequently, low amount of soluble contaminants were released from Nomex-910 solid dielectrics. Almost similar variations in IFT of DBPC inhibited oil samples were found over accelerated temperatures. Improvements in IFT of Nomex-910 impregnated oil samples over the samples having TUK are highly significant at 140^{0}C and 160^{0}C. It indicates the lower sludge formation of Nomex-910 mineral oil samples at these temperatures. In case of DBPC inhibited oil samples, such significant changes were observed at 200^{0}C and 220^{0}C. It represents that the rate of sludge formation is less in DBPC inhibited oil samples as compared to that of uninhibited mineral oil samples. Therefore, it has been determined that the mineral oil in conjunction with Nomex-910 solid dielectric is an alternative combination of transformers solid and liquid insulations in order to achieve lower sludge and sediments.

C. Water Content

Columetric Karl Fischer Titrator determines the amount of water content (WC) present within the transformer oil [28]. The water content present within the oil increases due to heat dissipation. Excessive water content results in the breakdown of the insulation [29]. This test is conducted as per the guidelines given in ASTM D 4643-08 [28]. Figure. 8 shows the test set up of Columetric Karl Fischer Titrator. Figure. 9 (a) and (b) shows the variation in water content of different oil samples subjected to accelerated temperatures. The percentage increments in water content of different test samples are shown in Figure. 10 (a) and (b).

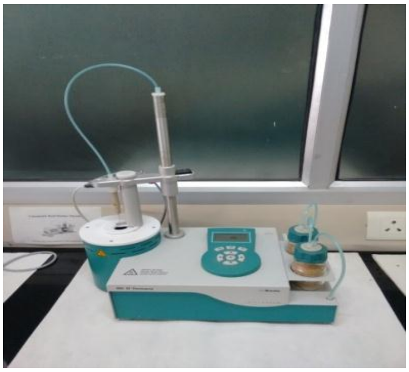
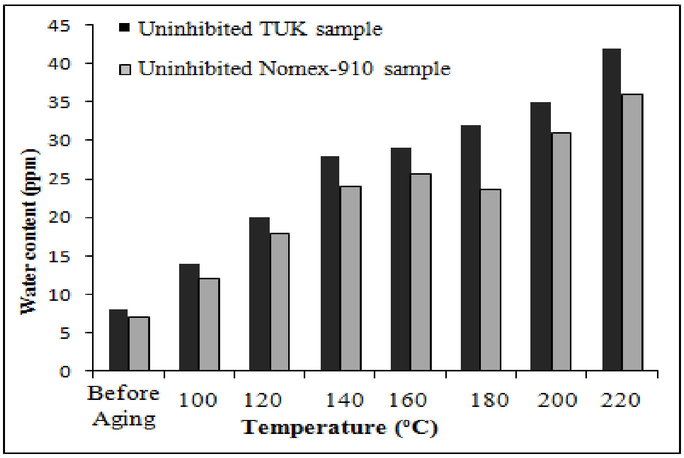


Figure 8. Columetric Karl Fischer Titrator set up installed at TIFAC-CORE centre, NIT Hamirpur.

In case of Nomex-910 mineral oil samples, the water content reaches to its excessive level at 200^{0}C. Consequently, the water content present in TUK mineral oils reaches the completely deteriorated level at 140^{0}C. A substantial increase in the water content of these samples was observed over the accelerated temperatures. This indicates the higher stability loss of these oils. It has been clearly observed from Figure. 9 that the water content present in TUK oil sample was increased rapidly as per the accelerated tests. The more the water exists in the oil the more the oil will decompose. Synthetic aramids present in Nomex-910 samples slower the oxidation rate of the test samples.



(a)

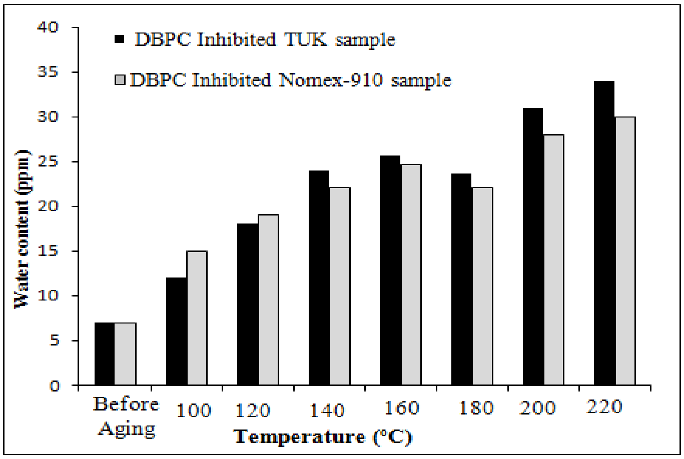


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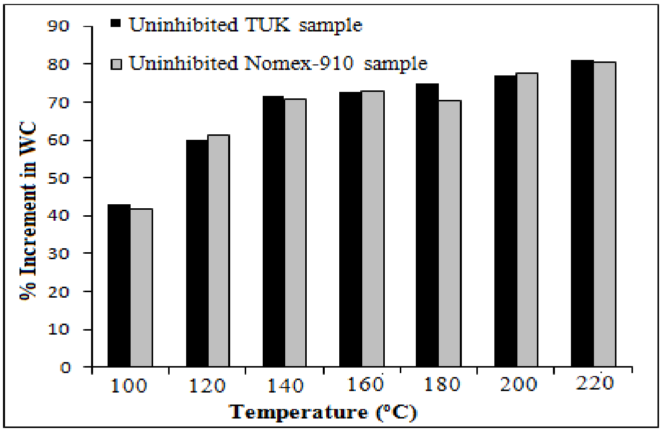
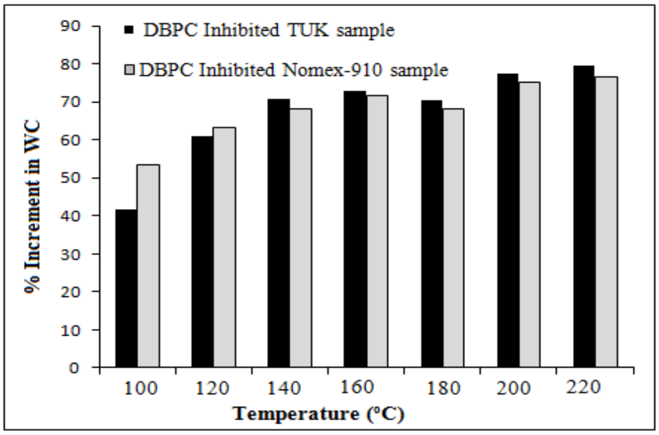
Figure 9. Variations in water content of (a) uninhibited and (b) DBPC inhibited mineral oil samples over accelerated thermal aging.



(a)



(b)

Figure 10. Percentage increments in BDV of (a) uninhibited and (b) DBPC inhibited mineral oil samples over accelerated temperatures.

Almost similar variations in water content of DBPC oil samples were observed. In these test samples, DBPC reduced the generation of water content even at higher temperatures. It indicates the improved thermal performance of DBPC inhibited mineral oils over uninhibited oil samples. However, the rate of increment in WC of these samples is lesser than that of TUK oil samples. Thus, mineral oil with Nomex-910 solid dielectric is the alternative combination of transformers insulation to have least amount of water content.

4. Conclusion

The present paper compares the operating performance of mineral transformer oil impregnated with thermally upgraded Kraft and Nomex-910 solid dielectrics. The test samples prepared for the experimentation of the present work have been thermally stressed at different temperatures ranging from 100^0C to 220^0C. It has been investigated from the accelerated aging analysis that the oil samples consisting of Nomex-910 dielectric have the better oxidation stability and the improved thermal characteristics than that of TUK based oil sample. Similar observations were found in case of accelerated thermal aging of 2,6-dibutyl-4-methylphenol (DBPC) inhibited mineral oil with different solid dielectrics. DBPC inhibitor added in the oil sample significantly improves the overall quality of the insulation, thereby improving its service life time. Though the expenditure of these Nomex paper is higher than TUK, however, these insulations have around 20% enhanced service life time with better thermal performance. Therefore, a huge revenue profit has been attained by utilities and customers.

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