Life Assessment of Power Transformers via Paper Ageing Analysis

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Abstract- **The status of insulation in electrical power equipment at any given point in time can be assessed by monitoring several properties which are sensitive to the amount of ageing. This procedure is commonly known as the diagnostic or non-destructive testing. For power transformers, the condition of the paper insulation can be assessed by an examination of the tracks provided by by-products of chemical dissociation of cellulose in solution with oil. This work addresses the need of paper insulation condition monitoring by determining the furfural contents in transformer oil using High Performance Liquid Chromatography (HPLC) technique. The degradation of electrical Kraft paper under laboratory ageing experiment was examined by means of assessing the increase of concentration of furan compounds as well as the increase of moisture content. Experimental results show that the thermal ageing process causes a proportional increase in 2-FAL furan compound as well as in moisture content. Both increases were shown to be related to the ageing or degradation of paper insulation.**

I. Introduction

For decades until now, manufacturers and end users alike have been absorbed by the challenge of extending the life span of power transformers. The life span of power transformers averages between 50 to 70 years, as the high capital cost of its replacement is astronomical. It is therefore essential that the utilization of the transformer can be optimized to the fullest extent of its maximum lifespan. It is generally accepted that the reliability of power and distribution transformers decreases with the ageing of their insulation system. This ageing is mainly due to the degradation of the characteristics of the insulating materials. In determining the life consumption of the transformer, measuring the degree of polymerization of the insulating paper is the more reliable way. However, this intrusive test requires a sample of the paper which means that the transformer has to be taken out from service and that portion of the unit be destroyed in the process. Therefore this method is not suitable for the transformers in service.

The operating conditions of power and distribution transformers and other oil filled electrical equipment are usually monitored by measuring dissolved gasses in the insulating oil using gas chromatography. The analysis of oil samples does not represent a significant difficulty. Most electrical equipment is provided with sampling valve and a number of physical and chemical analyses can be performed both in the field and in the laboratory to determine the oil condition. Moreover, the insulating oil is widely used in predictive maintenance because its degradation under faulty operating conditions such as thermal defects, arcing or partial discharges, will produce gases that partially dissolved by the oil and their analysis may indicate the type or severity of the fault.

The deterioration of transformer insulation is primarily a function of temperature and time, but it is also influenced by other factors such as moisture and oxygen content. Therefore, most predictive maintenance techniques of the transformer are focused on the monitoring of these factors. This is quite satisfactory for the assessment of the insulation conditions of the liquid. However, the techniques adopted such as the gas-in-oil analysis cannot give an account on the condition of the paper insulation. Similar sampling technique cannot be easily implemented with cellulosic paper due to the bad accessibility from the outside of the transformer tank. Therefore, a method of assessing the condition of the paper without involving the paper sample itself is required. An in-depth oil analysis had shown the presence of 2-fulfuraldehyde and related compounds, where these compounds are known to be specific to the degradation of cellulose and other paper constituents [1-3].

One such in-depth oil analysis is known as the High Performance Liquid Chromatography (HPLC). When the cellulosic insulation materials within a transformer undergo degradation, either by normal aging or by being involved with an incipient fault, among the by-products formed are carbon monoxide and carbon dioxide gases and derivatives of the aromatic compound called furan. Thus the amount of furans present in the oil might be a good indication of the cellulosic insulation condition.

In this work, the degradation of Kraft transformer insulation paper is examined by means of monitoring the increase in the concentration of furan compounds as well as the increase of moisture content.

II. Methodology

A. Samples

In this work, the ageing device in the form of a stainless steel test tube was designed according to IEEE Standard Test Procedure for Thermal Evaluation of Liquid-Immersed Distribution and Power Transformers (IEEE Std. C57.100-1999, as stated in the Annex A, clause A.2) [4].

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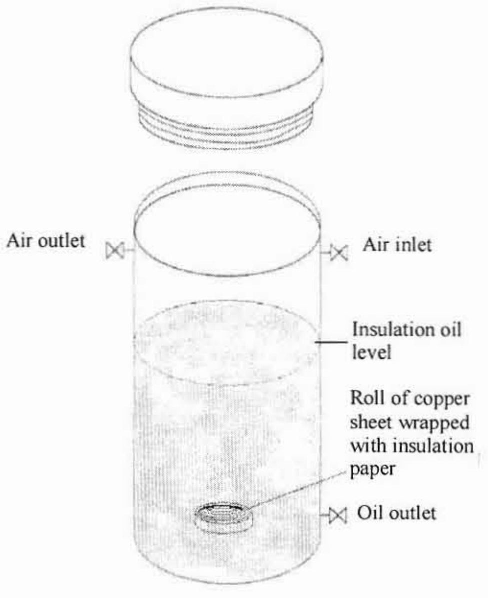

Fig. 1 The stainless steel design test tube used for the ageing tests

Fig. 2 An example of the actual stainless steel test tube used for the ageing tests

Each tube has a length of 28 cm, outer and inner diameters of 4.5 cm and 4.0 cm respectively, and a wall thickness of 5.0 mm. Fig. 1 shows the schematic diagram of the test tube. Fig. 2 shows an example of the actual test tube constructed. Fig. 3 shows the equipment used for moisture content measurement and the High Performance Liquid Chromatography (HPLC)

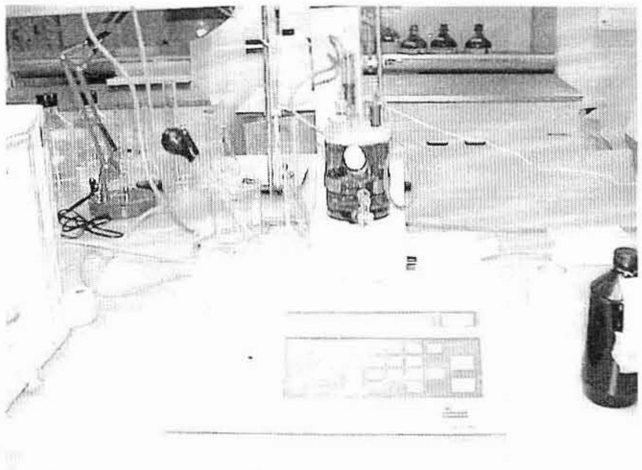

Fig. 3 Karl Fisher Moisture Meter

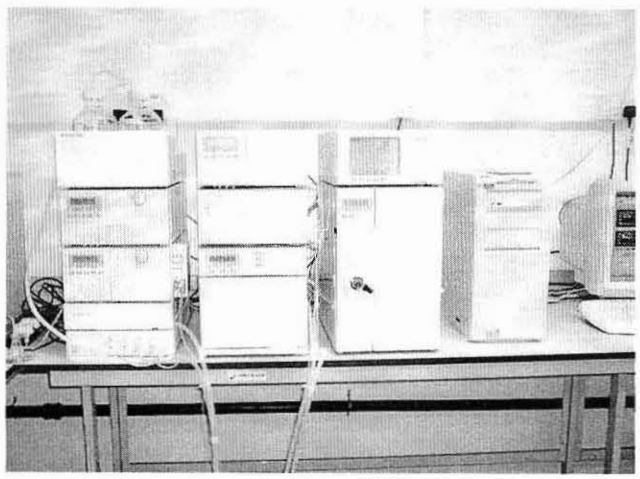

Fig. 4 High Performance Liquid Chromatography (HPLC)

system is shown in Fig. 4.

There were four similar ageing tubes used and they are labeled as follows:

i. Sample A contained a roll of Kraft insulation paper immersed in transformer oil.
ii. Sample B contained a roll of copper sheet wrapped with Kraft insulation paper immersed in transformer oil. The inclusion of the copper sheet in this test sample if for the purpose of monitoring the effect of copper presence to the furan content.
iii. Sample C contained transformer oil only.
iv. Sample D contained a roll of copper sheet and Kraft insulation paper immersed in transformer oil.

There were two sets of experiments. In the first set, Samples A, B and C were placed in a furnace at a temperature of 150°C and Sample D was kept at 30°C. The heating temperature of

150°C was for duration of 1000 hours. Oil samples were taken from each tube at every 200 hours and analyzed for their furanic and moisture contents. To do this, the Samples were taken out of the furnace and then were let to cool down to 65-85°C corresponding to transformer operating temperatures. After the required oil samples were extracted, the samples were quickly heated again in the furnace.

In the second set, Samples A, B and C were placed in a furnace at a temperature of 170°C and Sample D was kept at 30°C. The heating temperature of 170°C was for duration of 72 hours. The heating temperature was chosen based on [5] to simulate the accelerated ageing of the paper insulation. Furthermore, it is reported that ageing will not take place until a definite temperature (90°C) is exceeded [6]. Oil samples were taken from each tube at every 24 hours and analyzed for their furanic and moisture contents. To do this, the Samples were taken out of the furnace and then were let to cool down to 65-85°C corresponding to transformer operating temperatures. After the required oil samples were extracted, the Samples were quickly heated again in the furnace.

B. Ageing Parameters

In this study two parameters of ageing, namely, the furanic derivatives and the moisture content, were monitored. It is known that the thermal degradation of cellulosic materials occurs in electrical equipment such as power transformers. The degradation of the oil-paper insulation system yields different amounts of furanic derivatives such as 2-furfuraldehyde (2 FAL), 5hydroxy-methyl 2-furfuraldehyde (5H2F), 2-acetylfuran (2 ACF), 5-methyl 2-furfuraldehyde (5M2F), and furfurylalcohol (2 FOL) and furoic acids. The 2-furfuraldehyde (2 FAL) is the most common derivative found.

Apart from high temperatures, moistures are known to be the arch enemy of solid insulations. Moistures in combination with heat can degrade and hence shorten the life span of solid insulation of high voltage equipment.

III. Results And Discussion

Table 1 shows the results on the analysis done to determine the furan and moisture contents of all samples for Set 1 (Heating temperature - 150°C/1000hrs). It can be seen that the concentration of furfural absorbed in paper increases with the ageing duration. The tabulated data shows out of five furanic compounds measured, only 2 FAL, 2 FOL and 5H2F managed to be detected at all. The results show that the contents of furan compounds in the oil sample are not consistent except for the 2-FAL furan. Fig. 5 shows the variation of 2-FAL furanic compound with ageing duration for Samples A, B and C. It can be seen that the concentration of furfural produced increases with the ageing duration. The effect of copper is negligible. There is no furanic compound detected in the oil only sample (Sample C). Fig. 6 shows the corresponding variation of moisture content with ageing duration for the same samples. Again, the increase in moisture content in Samples A and B, as compared to oil only Sample C, can be concluded to be due to paper degradation.

Fig. 7 shows the relationship between the moisture content and the 2-FAL furan content as the ageing duration increases. The ageing process is seen to cause a proportional increase in both moisture and 2-FAL furan for Sample B (paper and copper).

Table 2 shows the results on the analysis done to determine the furan and moisture contents of all samples for Set 2 (Heating temperature - 170°C/72hrs). The tabulated data shows out of five furanic compounds measured, only 2 FAL, 2 FOL and 5HMF managed to be detected at all. It also shows inconsistent results for all furanic compounds except for 2 FAL compound. This confirmed the results found in a previous work [1] where laboratory experiments and field experience have shown similar instability except for the 2-FAL furan.

Fig. 8 shows the variation of 2-FAL furanic compound with ageing duration for all samples. It can be seen that the concentration of furfural absorbed in paper increases with the ageing duration. However, there was a reduction in 2-FAL content at 72 hours ageing. The main reason of this is because

Table 1 Furan analysis and moisture content results due to thermal accelerated ageing for all samples. Sample D is the controlled sample and kept at 30°C. (Set 1 – Heating temperature 150°C/1000hrs)

Sample ID	Ageing Hours	Furanics compounds (part per billion)						Moisture content (ppm)
		2 FOL	5 H2F	2 FAL	2 ACF	5 M2F	TOTAL	
Sample A	0	0	0	0	0	0	0	12
	200	0	0	44	0	0	44	20
	400	51	41	54	0	0	54	47
	600	33	52	68	0	0	68	56
	800	0	3	201	0	0	204	80
	1000	0	133	300	0	0	433	102
Sample B	0	0	0	0	0	0	0	12
	200	0	0	74	0	0	74	20
	400	0	0	83	0	0	83	34
	600	0	0	96	0	0	96	43
	800	0	11	213	0	0	224	92
	1000	0	147	316	0	0	463	156
Sample C	0	0	0	0	0	0	0	12
	200	0	0	0	0	0	0	24
	400	0	0	0	0	0	0	33
	600	0	0	0	0	0	0	37
	800	0	0	0	0	0	0	46
	1000	0	0	0	0	0	0	50

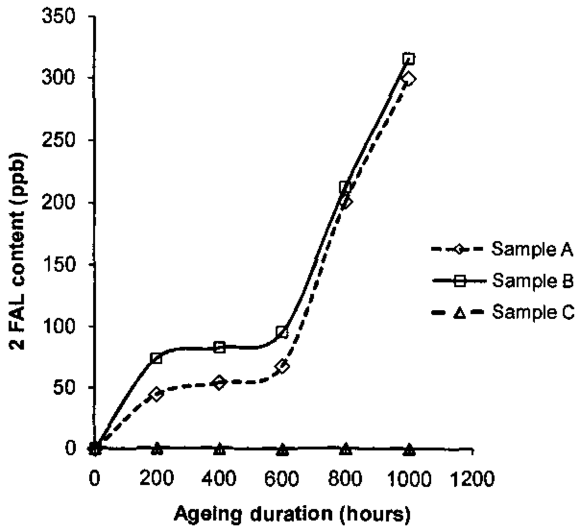

Fig. 5 The variation of 2 FAL furan compound content with ageing duration (Set 1 - Heating Temperature 150 °C/1000hrs)

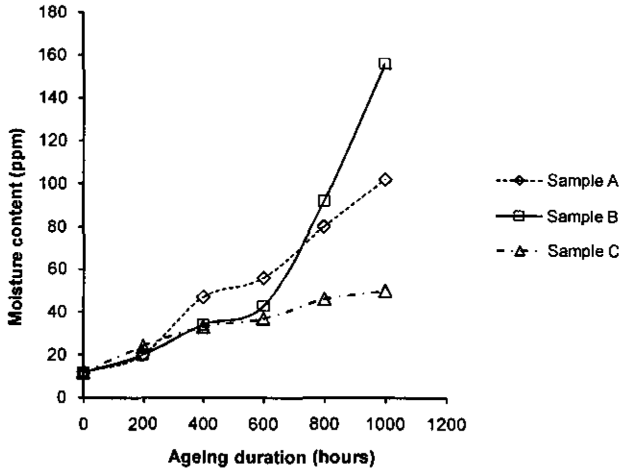

Fig. 6 The variation of moisture content with ageing duration (Set 1 - Heating Temperature 150°C/1000hrs)

of the elapsed time allowed for the oil sample to be extracted after reaching the 65-80°C temperature range for the case of after 72 hours ageing, where all aged Samples were left for 36 hours before oil samples were drawn. It is noted that some of the furans produced due to ageing are absorbed back by the paper insulation and hence causing an overall reduction in furan contents with ageing duration.

Fig. 9 shows the corresponding variation of moisture content with ageing duration for the same samples. It is known that the furfural has the ability to migrate back and forth between the mineral oil and the paper insulation. Thus, the furan

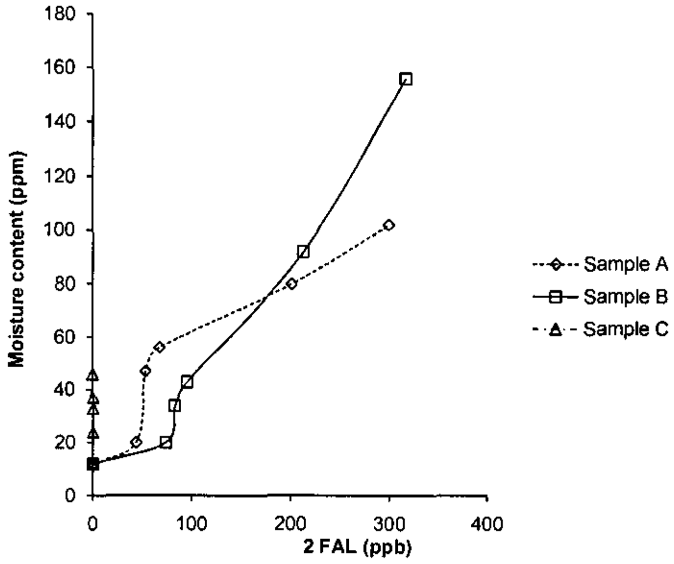

Fig. 7 Relationship between moisture content and 2FAL as ageing duration increases (Set 1 – Heating temperature 150°C/1000hrs)

Table 2 Furan analysis and moisture content results due to thermal accelerated ageing for all samples. Sample D is the controlled sample and kept at 30°C. (Set 2 – Heating temperature 170°C/72hrs)

Sample ID	Ageing Hours	Furanics compounds (part per billion)						Moisture content (ppm)
		2 FOL	5 H2F	2 FAL	2 ACF	5 M2F	TOTAL	
Sample A	0	0	0	0	0	0	0	12
	24	336	69	152	0	0	557	55
	48	51	41	196	0	0	288	51
	72	33	52	181	0	0	266	32
Sample B	0	0	0	0	0	0	0	12
	24	81	15	119	0	0	215	45
	48	87	73	137	0	0	297	48
	72	11	38	50	0	0	99	31
Sample C	0	0	0	0	0	0	0	12
	24	0	0	0	0	0	0	46
	48	0	0	0	0	0	0	52
	72	0	0	0	0	0	0	128
Sample D	0	0	0	0	0	0	0	12
	24	0	0	0	0	0	0	26
	48	0	0	0	0	0	0	29
	72	0	0	0	0	0	0	31

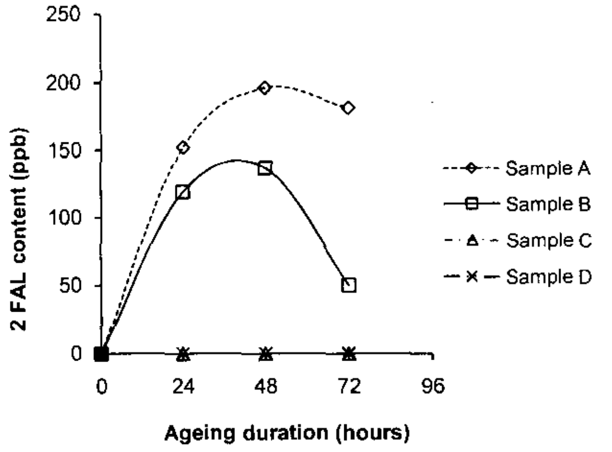

Fig. 8 The variation of 2 FAL furan compound content with ageing duration (Set 2 – Heating temperature 170°C/72hrs)

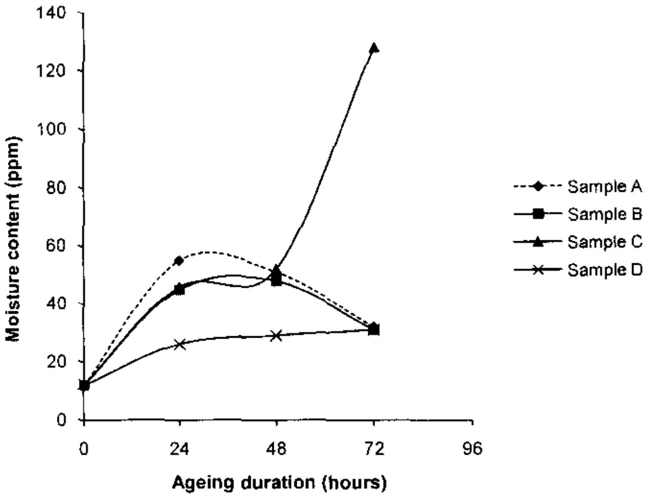

Fig. 9 The variation of moisture content with ageing duration (Set 2 – Heating temperature 170°C/72hrs)

concentration tends to fluctuate within ±15% when the actual experimental data collection is carried out within several months period. Such fluctuations are due to normal response to changes in the condition within the transformer [2]. Moreover the furfural is a polar compound which requires time and particular conditions to be released into the oil [3].

Fig. 10 shows the relationship between the moisture content and the 2-FAL furan content as the ageing duration increases. The ageing process is seen to cause a proportional increase in both moisture and 2-FAL furan for Sample B (paper and copper). As for Sample A (paper), the proportionality is disrupted due to the decrease in 2-FAL content at the 72 hours duration.

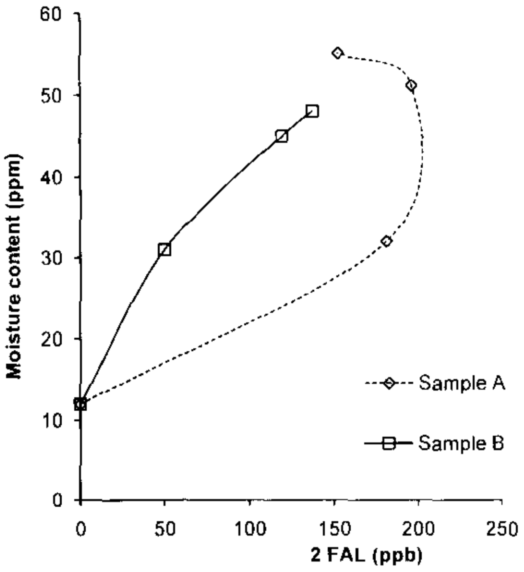

Fig. 10 Relationship between moisture content and 2FAL as ageing duration increases (Set 2 – Heating temperature 170°C/72hrs)

IV. Conclusion

The analysis of furanic compound dissolved in the oil of in-service transformers is a powerful tool for condition monitoring of oil-paper insulating systems. Furthermore, it can also provide complementary information to the usual dissolved gas analysis (DGA) technique. Paper and oil degradation experiment under very well defined laboratory conditions indicates that furanic compounds, especially furfural and hydroxymethylfurfural, as well as moisture content, can be used as an indicator of the ageing degree of the insulation paper. These by-products are be formed due to cellulose degradation.

Active overheating and ageing of the solid insulation can reduce equipment life. Proper maintenance and changes in operating conditions can be instituted to extend equipment life and maximize the use of valuable assets. It is also learnt that the life assessment using furanic compounds data can be used to prioritize equipment for removal and replacement. The results of this work can be further utilised for consideration in preventive maintenance program and to estimate equipment ageing for the purpose of replacement of equipment.

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