An assessment of the potential for oil flow damage in Kraft paper under normal operation and reclamation in a high voltage transformer

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***Abstract*—Thermal aging and UV irradiation are used as methods to prepare samples of Kraft paper spanning its full lifecycle within a high voltage transformer, from new to end of life. The mechanical break strain is correlated to the DP value, representing a progressive deterioration of mechanical properties during aging. Subsequent exposure to oil flow mimicking both normal plant operation and reclamation activities, shows that aged paper exposed to high rates of flow experiences noticeable surface roughening. Despite this, no measurable erosion occurs even after long term temperature/flow cycling in used mineral oil containing a notable particulate content. This indicates that Kraft paper is unlikely to be eroded by normal reclamation activities, even in a severely aged asset. This confirms the validity of using this approach to extend plant life.**

***Index Terms*— Aging, DP, Kraft Paper, Mechanical properties, Reclamation**

I. Introduction

IN a typical high voltage transformer, the copper windings are lapped with Kraft paper, assembled into the form of stacked disks, and are then inserted into a tank containing mineral oil. During operation, oil is circulated over this arrangement and then through an external radiator, either by natural convection (ON) or by pumps (OF), allowing waste heat to be safely dissipated.

Industry based studies have shown that a major cause of transformer faults is deterioration of the paper [1, 2] and therefore monitoring its condition is critical to ensuring safe and reliable transformer operation. However, due to the obvious inaccessibility of the paper during normal service, indirect techniques that rely on sampling the oil, rather than the paper, are routinely used to monitor plant health [2, 3].

A direct indicator of the condition of Kraft paper is its degree of polymerization or DP [4], this typically ranges from 1100 (new paper) to ~200 (end of life) [3, 5, 6] whilst values of 300 - 500 are typical for a decommissioned asset [7]. Kraft paper is mechanically anisotropic and the break strain is approximately halved in the fiber or longitudinal direction as opposed to the cross-fiber or transverse direction [8]. Its mechanical modulus is reportedly unaffected by aging [9] but its break strain falls significantly, representing a progressive embrittlement [1, 8] until eventually, Kraft loses all mechanical integrity for DP ≤ 200 which corresponds to a break strain of < 1 % [1, 10].

Deteriorated paper can compromise plant health in various ways; for example, it may not be able to withstand the electromechanical forces inherent to normal transformer operation [11]. Alternatively, paper fragments can break away from the windings and block oil ducts, compromising cooling efficiency. Furthermore, a loss of winding insulation can lead to short circuits [4] and it is easy to envisage scenarios whereby paper deteriorated by aging could be eroded by oil flows, again compromising insulation integrity. Under normal operation of the transformer (ON) oil velocities are low, typically < 0.05 m/s at the paper [12], but during periods of high electrical demand when the cooling pumps are switched on (OF), oil velocities of up to 0.4 m/s are expected [13]. Furthermore, with aging oil, reclamation (RC) is becoming more commonplace for restoring oil properties and is regarded as a life-extending activity for transformers [14, 15]. During reclamation, oil is pumped through the asset at ≥ 2000 l/h, resulting in much higher oil velocities of ≥ 1 m/s (dependent on the transformer design and size) and hence, a much greater potential for insulation damage exists. Clearly, having an understanding of the consequences of imparting oil flows, simulating both normal transformer operation and reclamation, over a paper surface in a known condition, will assist network operators in making better asset management decisions, particularly when reclaiming older units.

Such investigations require the preparation of Kraft paper samples with mechanical properties spanning its entire lifecycle. This requires a methodology of aging paper in the laboratory which is representative of aging in the asset. Temperatures > 160 ºC should be avoided as they lead to pyrolysis [5, 8, 16, 17] whilst at lower temperatures, in the absence of oxygen, breakage of glycoside bonds occurs liberating water, CO and CO_2 [17]. In the presence of oxygen, additional by-products such as carboxylic acids and ketones may be produced which can accelerate the aging process [5, 6,

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18, 19]. Interestingly, aging at temperatures much below 110 °C [5, 16, 17, 18, 19] results in the DP failing to reach 200 which is the required end of life condition [6]. Therefore, to provide suitable samples requires aging at temperatures between 150 °C and 110 °C for 2 to 12 weeks [3, 5, 19, 20, 21, 22]. A fan oven is the simplest way of aging paper in the laboratory and ensures that it is kept dry and that any by-products are efficiently removed [1, 2, 16]. In contrast, aging under oil is more complex as the oil is aged at the same time as the paper and can contribute free water and carboxylic acids, which can further accelerate the aging of the paper [18, 19, 20, 21].

To avoid such complications, the authors have elected to use a fan oven and our previous investigations [23] have shown that this methodology provides suitable samples exhibiting minimal oxidation. Oil flow testing [24], which to our knowledge has never been undertaken previously on Kraft paper, then showed that the surface texture of aged paper can be disrupted by high rates of oil flow; however, at the low oil temperatures and short exposure times, which are far from conditions in a working transformer, there was no detectable erosion. This was also true for ultraviolet (UV) irradiated samples, which have a very low value of surface DP (mimicking severe aging in plant), after only a few days of exposure [25]. In this report, this earlier work is significantly expanded by considering short-term flow testing at the more representative oil temperature of 60 °C, before moving on to summarize results from longer term oil flow testing, which is more representative of reclamation activities.

II. Experimental

Kraft paper, non-thermally upgraded type 1.2-1M (IEC 60641-1) with a specified thickness of 4 mil was used throughout. 10 x 10 cm samples were aged in fan ovens at 110, 130 and 150 °C. Alternatively, ultraviolet C (UVC) irradiation was carried out using the same equipment as used previously (wavelength 254 nm, intensity 4 mW/cm^2) [25]. DP measurements were then performed according to ASTM D4243 [4] using 15 mg samples dissolved in 20 ml of 0.5 M Bis(ethylenediamine) copper (II) hydroxide solution (Sigma Aldrich). Five measurements of viscosity using a glass viscometer tube (C = 0.01 cSt) held at 20 ± 1 °C allowed the average DP to be determined according to the standard. A theoretical model [25] then allowed the surface DP of the UVC irradiated samples to be calculated from the measured values.

Mechanical testing (ASTM D828-16) was undertaken on strips 70 x 15 mm in size. The break strain was measured on at least three separate samples in the fiber (longitudinal or L) direction as well as in the cross-fiber (transverse or T) direction. All measurements were performed on the same day, to prevent variations in humidity from affecting the results [8]. A Tinius Olsen H25KS tensiometer with a gauge length of 50 mm and a crosshead speed of 10 mm/min was used (humidity 45 ± 2 %, temperature 22 ± 1 °C).

Following aging, the paper was impregnated by submerging in new mineral oil (Nynas Gemini X) in glass jars and drawing vacuum until all visible signs of bubbling had stopped (typically 1 h). A bespoke oil flow tester, based on the concept of a recirculating oil bath, was constructed to expose the samples to oil flow and has been described in detail elsewhere [24, 25]. A pump (Jabsco, 40 size) circulates the oil whilst an 800 W heater maintains the oil at 60 °C; a temperature appropriate to plant. A bypass valve installed across the pump controls the flow rate, which was measured using a flow meter and an Arduino based system was used to control the heater and log data.

A laminar flow model was implemented in COMSOL and the chosen geometry, consisting of a tilted plate onto which the sample was attached using a metal shim, resulted in a uniform oil flow field across its surface (Fig. 1a) where the incoming oil jet (arrowed) shows a flattened cross-section at the sample (Fig. 1b). The modelling was also used to establish the relationship between the oil velocity at the sample and the flow meter reading. In line with our previous work [24] and considering appropriate oil velocities at the paper [12, 13, 14, 15], flow rates of 3, 12 and the maximum available flow rate of 35 l/min were used to simulate ON, OF and RC conditions respectively. A testing cycle was 6 h to fit into the working day which allowed time (30 min) to heat the oil to temperature.

Following testing, the samples were extracted by submerging them gently in a bath of acetone for at least 1 h. They were then removed, placed on absorbent material to dry and left under ambient conditions for at least 24 h to regain their

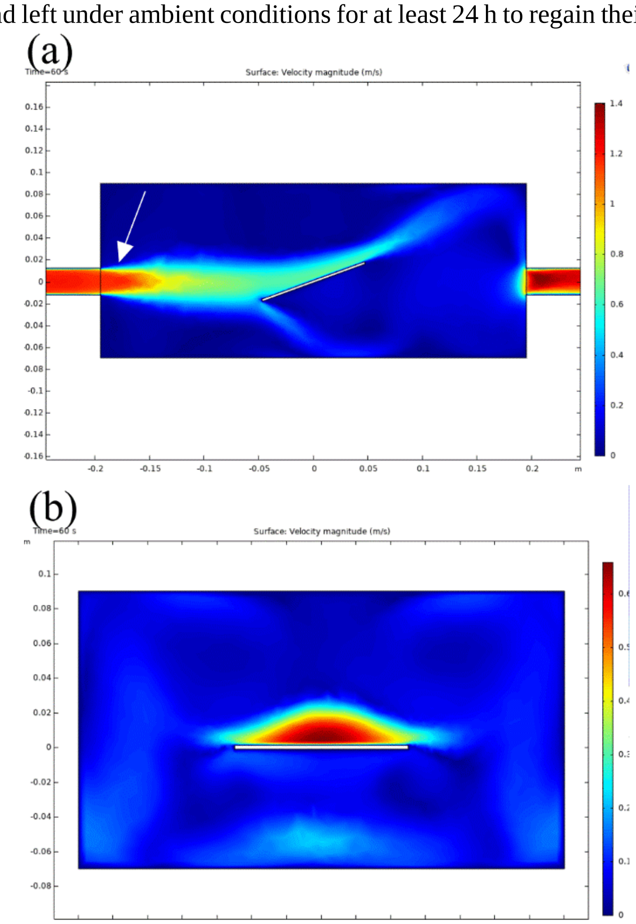

Fig. 1. Oil velocity profiles from COMSOL simulation at an oil temperature of 60 °C showing (a) oil jet (arrowed) entering from the left and flowing over the sample, (b) cross sectional view of oil jet at the sample. Images not to the same scale.

original moisture content. Optical microscopy was then performed using oblique illumination on a 4 MP digital microscope. Finally, measurements of sample thickness were performed according to ISO 534 in ten different areas; the data were input into Microsoft Excel and processed to determine if any statistically significant flow related erosion had occurred.

III. Results

A. Initial characterization

Effect of aging on DP. The DP (Fig. 2a, typical uncertainty ± 20) falls with aging time and aging is accelerated at higher temperatures. A fit of the experimental data to the published rate equation [1];

$$\frac{1}{DP_t} - \frac{1}{DP_o} = \frac{K_{10}}{K_2}\left(1 - e^{-K_2 t}\right) \quad (1)$$

where DP_t is the DP of the sample at time t, DP_o is the initial DP and k_{10} and k_2 are rate constants, is shown in Fig. 2b and the excellent correlation ($r^2 > 0.98$) validates our approach of using fan ovens to undertake aging.

The rate constant k_2 is decreased at lower aging temperatures [22] and the values of 0.061, 0.019 and 0.007 show that the aging rate decreases by a factor of 3 per 20 ºC drop in temperature. At temperatures of 150 and 130 ºC the ratio k_{10}/k_2 is 4 x 10^{-3} whilst at 110 ºC it is 2 x 10^{-3}. This value determines the value of DP at long aging times (as t → ∞) and results in a very reasonable value of 200 [6] for 150 ºC and 130 ºC. The higher minimum DP of 350 for 110 ºC confirms that this temperature is insufficient to access the lowest DP values [5, 16 - 18].

Fig. 2c shows, as data points, the measured DP from the UVC exposed samples as a function of irradiation time. The predictions of the model [25] both in terms of average DP (which fits the measured data very well) and surface DP are shown as the solid lines. Clearly UVC exposure provides a novel and energy efficient way of obtaining samples with a very low value of surface DP, simulating the condition of paper in a severely aged asset, within only a few of days of exposure.

Effect of aging on mechanical properties. The break strain was higher in the cross-fiber (transverse) direction than in the fiber (longitudinal) direction as anticipated [8] and following aging, the break strain was reduced. Since examples of the raw data are provided elsewhere [23], for brevity, Fig. 3 shows the correlation [9] between break strain and measured DP which holds for both thermal aging and UVC exposure. When the DP is 500, the break strain is just under half of its original value [8] and when the DP falls to ~250, the break strain is ~1 % corresponding to end of life [1, 6, 10]; the paper can then be easily broken apart by hand. Clearly, either methodology (thermal aging or UVC irradiation) provides the required paper samples with deteriorated mechanical properties.

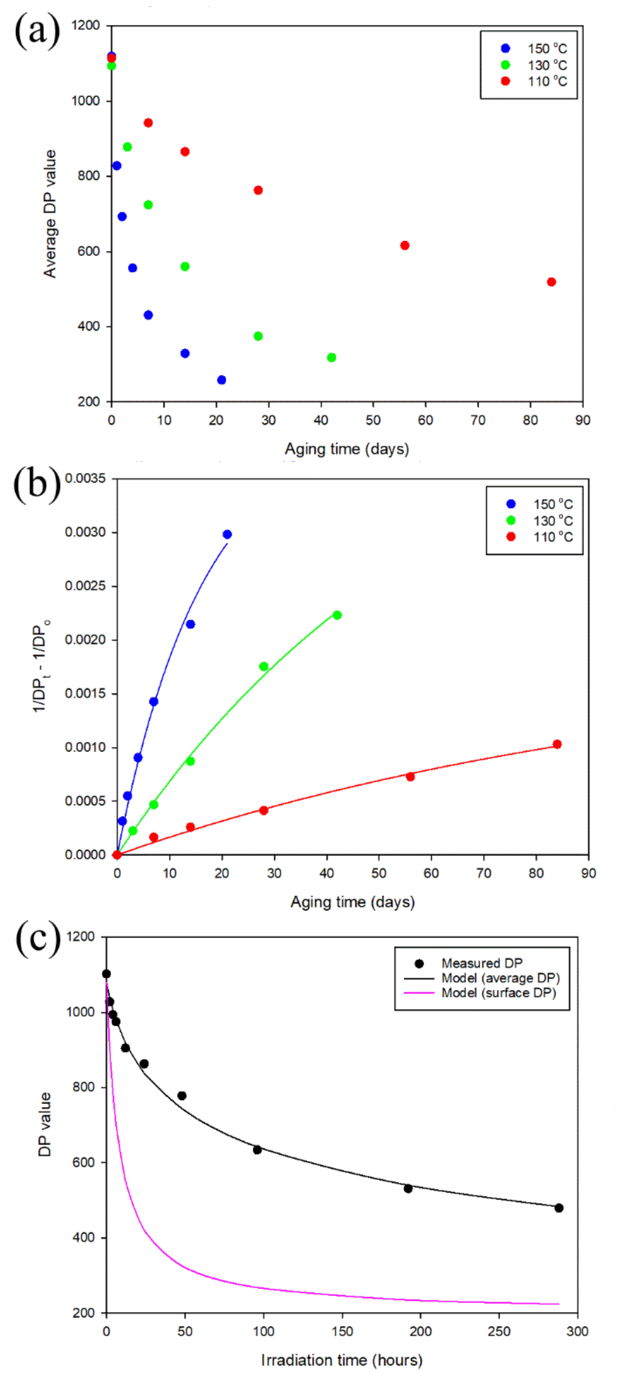

Fig. 2. Results from DP measurements (a) thermally aged samples, (b) fit to theory, (c) UVC irradiation and model predictions.

B. Short term oil flow testing

A selection of paper sheets were aged, either thermally (at 150 ºC for up to 21 d) or under UVC radiation (up to 288 h) and typical DP values for these are provided in Table 1. The samples were then exposed to oil flow for 6 h at 60 ºC and this section provides a summary of the key findings.

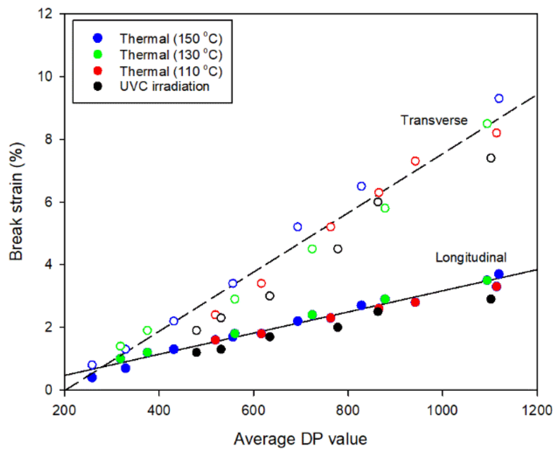

Fig. 3. Correlation between the average DP and mechanical break strain in both measuring directions for both methods of aging.

It was found that the extent of the oil flow related damage was not dependent on the oil flow direction relative to the fiber direction of the paper (either longitudinally (L) along the fibers or transverse (T) to this direction) but only depended on the DP of the paper and the oil flow rate. Therefore, the samples were ranked using a simple color scheme (Table 1) [24, 25] according to the visual change in surface texture (blue = no change, green = slight change, red = major change) and examples of each of these textures are shown in Fig. 4.

TABLE I
RANKING TABLE (DPM = MEASURED DP, DPS = CALCULATED SURFACE DP).

Aging	DPm	DPs	ON	OF	RC
New	1100	-			
150ºC, 4d	560	-			
150ºC, 14d	330	-	Fig. 4a	Fig. 4b	
150ºC, 21d	260	-			
UVC 36 h	780	360			Fig. 4c
UVC 96 h	640	270			
UVC 288 h	500	220			

Paper in all conditions exposed to oil flow rates consistent with convective cooling (ON) did not show any noticeable flow related damage (blue ranking). Even in severely aged samples (following thermal ageing at 150 ºC for 14 d, DP ~ 330), the observed surface textures (Fig. 4a) are consistent with that of new paper (since aging did not result in any observable changes in surface texture). These show distinctive "furrows" oriented along the fiber direction (from top left to bottom right in the micrographs) which arise from the manufacturing process. In contrast, exposing the same severely aged paper samples to oil flow rates consistent with forced cooling (OF) reveal "slight damage" (green ranking, Fig. 4b) where the furrows are noticeably less distinct in appearance. This ranking also applies to new paper (DP ~1100) and less severely aged paper (4 d at 150 ºC, DP ~ 560) exposed to oil flows consistent with reclamation. (Table 1). The remaining samples show the disrupted texture represented by Fig. 4c (red ranking); here we suggest that mechanical erosion of fine pulp material has occurred largely erasing the original furrows and resulting in a noticeably roughened surface texture which exposes many of the underlying fibers. This ranking applies to thermally aged samples with a DP < 350 as well as to all of the UVC irradiated samples despite them having much higher values of measured DP (Table 1). Assuming that the value of DP is independent of depth into the paper in thermally aged samples (DPm = DPs), this finding shows that the value of surface DP, rather than the measured (or average) DP, controls the extent of oil flow related damage. The ranking scheme

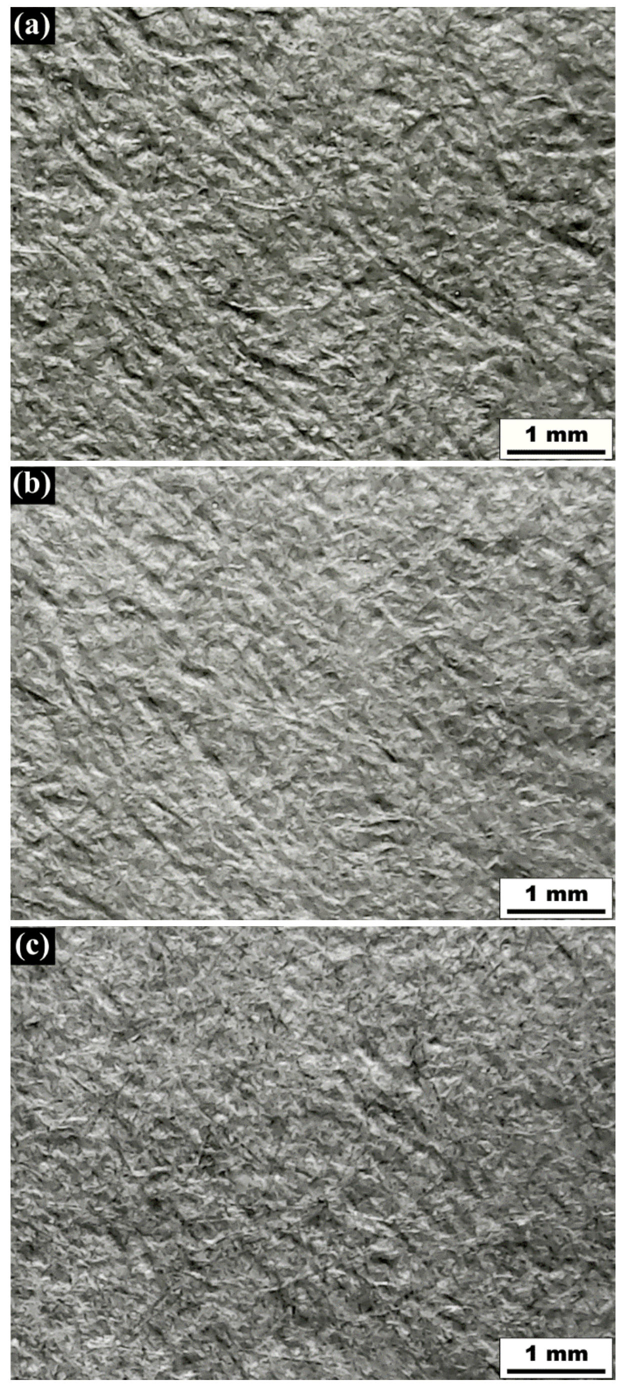

Fig. 4. Typical surface morphologies of oil flow exposed paper samples (a) blue ranking, (b) green ranking, (c) red ranking.

(Table 1) is entirely consistent with the earlier work undertaken at an oil temperature of 40 ºC.

Fig. 5 shows the corresponding measurements of sample thickness. New paper has an average thickness of 95 µm and, since the samples were always held under ambient conditions for at least 24 h before measuring, the slight reduction of thickness (~3 µm) following thermal aging (Fig. 5a) is unlikely to be due to changes in moisture content, rather it may reflect a loss of material during aging [17]. The observed scatter, which arises primarily from point-to-point variations in sample thickness (± 5 µm), is exemplified by considering the two sets of independent measurements on new paper and clearly dominates over any flow related effects. The observed changes in surface texture shown in Fig. 4 are therefore confined to the surface layers (< 2 µm) of the paper.

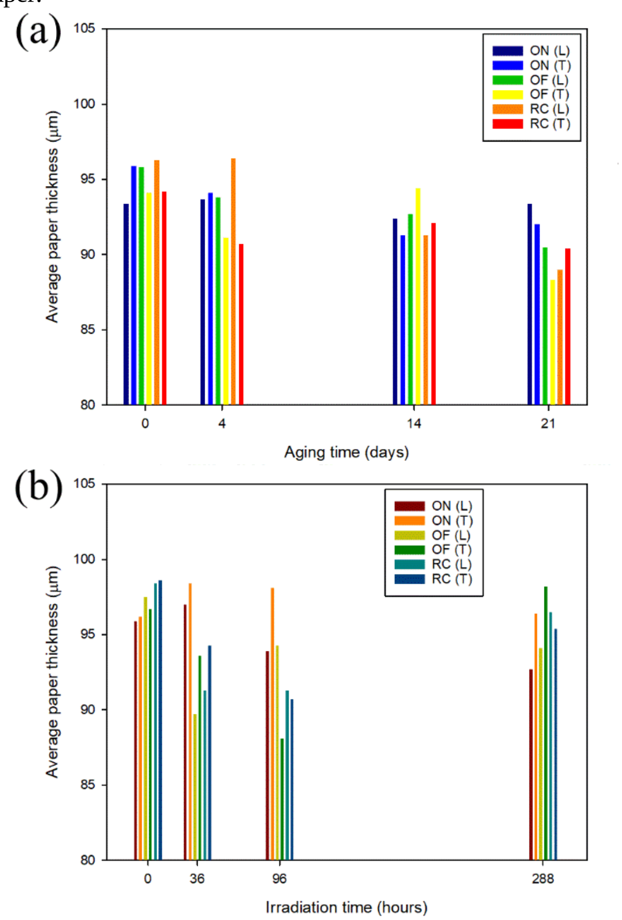

Fig. 5. Results from thickness measurements obtained from the (a) thermally aged samples, (b) UVC irradiated samples. L = longitudinal oil flow, T = transverse oil flow.

C. Long-term oil flow testing

To determine if any flow related erosion occurs under longer term temperature/flow cycling which would be appropriate to reclamation activities on severely aged assets [14], further 6 h flow cycles were performed on samples aged for 21 d at 150 ºC (DP ~ 250). Tests were undertaken over a total of 4 or 8 days (each day being 6 h exposure) and here the new mineral oil was replaced with used mineral oil removed from aged plant which was noticeably cloudy and yellowed in appearance.

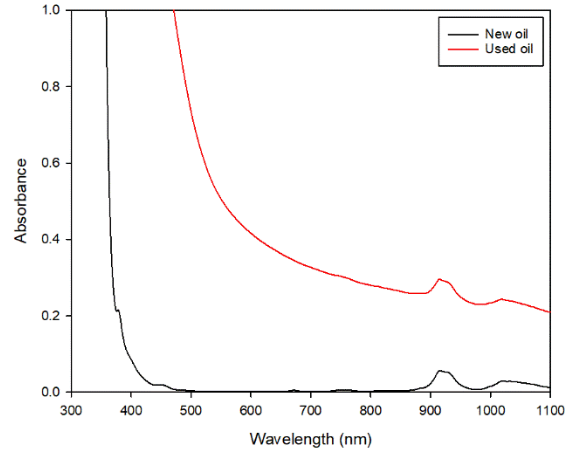

Fig. 6. Optical absorption spectra taken from both the new and aged mineral oils.

Optical absorption spectra were taken from both oils using a 10 mm quartz sample cell and a Perkin Elmer Lambda 35 spectrometer. The results (Fig. 6) confirm the anticipated absorbance arising from optical scattering of the particulates in the aged oil. The replacement oil thereby provides a much more realistic simulation of the oil condition in an aged asset where the particulate content could result in additional erosion of the paper.

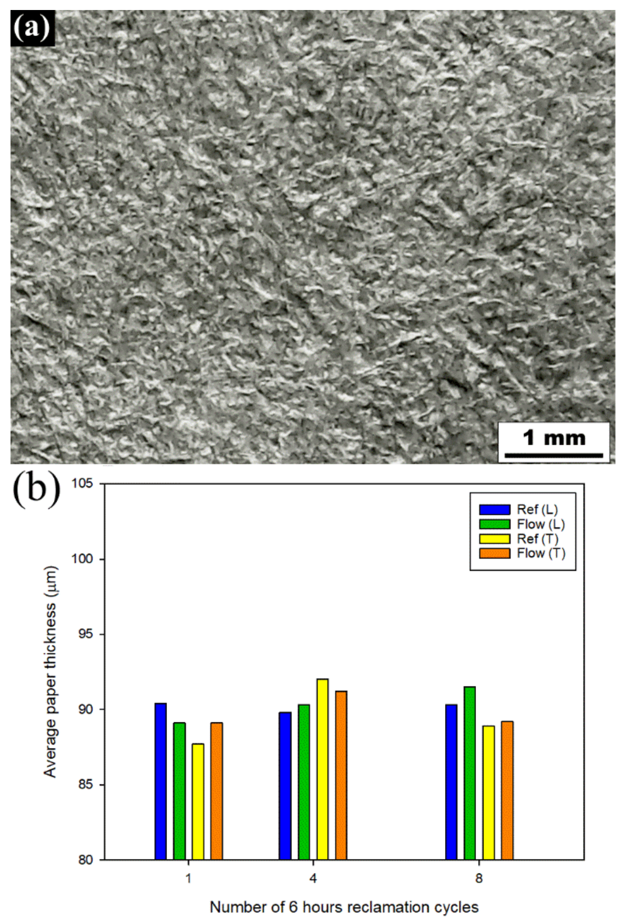

Fig. 7. Results from long-term oil flow exposure of aged samples (a) typical surface morphology after 8 cycles, (b) measured thicknesses.

Fig. 7a shows a representative micrograph of the surface textures obtained from this testing regime. The observed fine disrupted textures are consistent with those from the previous set of aged paper samples exposed to oil flows simulating reclamation conditions (see Fig. 4c) and crucially, the current samples show no evidence of tearing or pitting. Fig. 7b shows the results from thickness measurements where measurements taken from the above short-term (6 h) tests are included as data for 1 cycle. To provide a more rigorous comparison, measurements were undertaken in regions of the paper directly in the oil jet ("Flow") as well as in adjacent regions located under the metal shim ("Ref") which would not see any significant oil flow. Even under these longer-term tests, there is still no measurable thickness erosion, which provides strong support to the assertion that normal reclamation activities are unlikely to cause any oil flow related damage, even in a highly aged asset containing a particulate laden oil.

D. Copper bar samples

To further validate the key conclusion of this work, a final long-term oil flow test was undertaken in used oil with a geometry which approximates part of a transformer winding. A stacked arrangement of three 15 mm diameter copper bars separated by a gap of 5 mm was arranged behind an aluminum frame and replaced the original tilted plate sample holder. COMSOL modelling of this geometry (Figs. 8a and 8b) shows that it results in the expected non-uniform oil flow field [12, 13] and a complete disruption of the oil jet observed in Fig. 1. Using a flow rate appropriate to reclamation (35 l/min), the maximum oil velocity of 0.65 m/s (which is identical to that seen at the surface of the flat sheet samples with the same flow rate, see Fig. 1b) is only seen between adjacent bars (Fig. 8b) with lower flow rates evident elsewhere.

To carry out the oil flow testing experiment, paper aged for 14

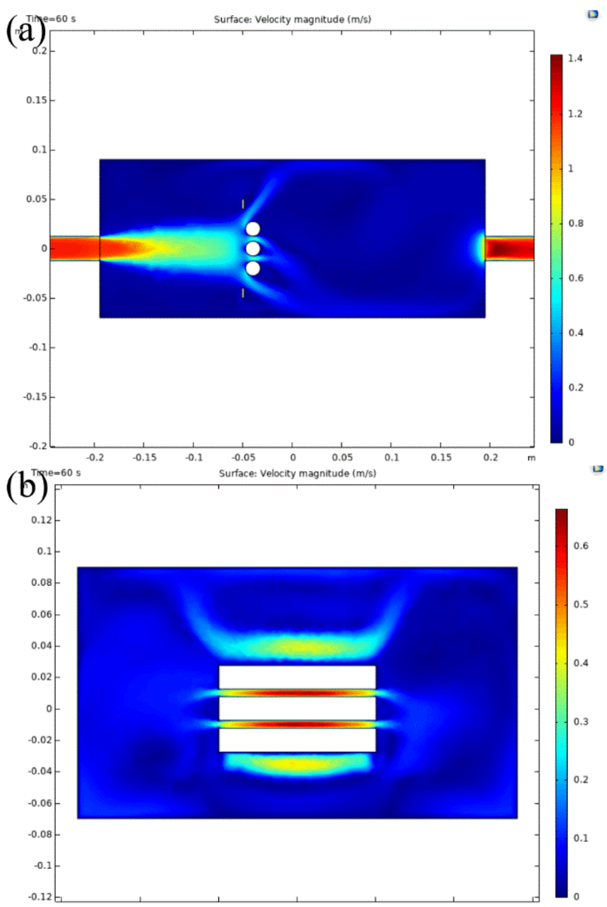

Fig. 8. Results from COMSOL modelling of the copper bar sample geometry (a) side view, (b) cross-section view in plane of the bars. Images not to the same scale.

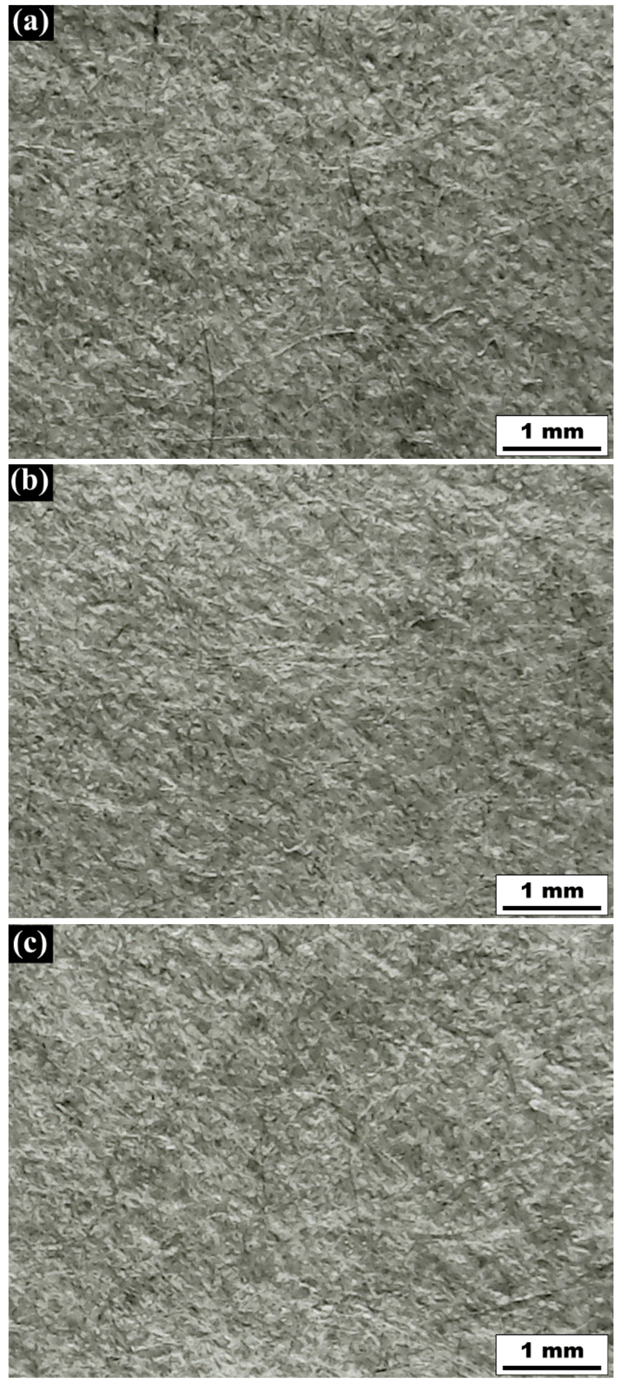

Fig. 9. Surface textures from paper wrapped around the middle bar (a) bottom surface (b) front surface (facing the oil inlet), (c) back surface.

d at 150 °C (DP ~300) was used as the extreme brittleness of the 21 d aged paper caused it to crack when wrapped around the copper bars. This was wrapped around the bars and secured in place with cable ties. Fig. 9 shows representative surface textures obtained after flow testing (8 x 6 h cycles) of the paper wrapped around the middle bar which most accurately mimics an internal section of a transformer winding. Considering first the area of paper located between adjacent bars, which sees the highest rate of oil flow, a highly disrupted surface texture with evidence of detached fibers was observed as expected (Fig. 9a). Surprisingly, the paper surface directly exposed to the oil jet (Fig. 9b) and even more surprisingly, the surface located behind the bar away from the oil jet (Fig. 9c), both show identically disrupted textures despite the computational model predicting significantly lower oil flow rates in these areas. This was confirmed by examining the surface textures of the paper attached to the upper and lower bars and shows that the surface roughening is surprisingly uniform. This unexpected finding is most likely due to the effects of turbulent flow, for example vortex shedding, which is not explicitly modelled here.

To confirm whether any measurable erosion has taken place in this more representative geometry, measurements of thickness were made in various radial positions along with reference measurements ("Ref.") performed on an underlying region of paper which had not been exposed to oil flow. Fig. 10 provides a summary of the results for 4 x 6 h cycles (bars 1 – 3 representing paper taken off the top, middle and bottom bar respectively) and 8 x 6 h cycles (bars 4 – 6) tests. There is no statistical variation in any of the measurements from the respective reference values. This confirms that the observed disruption to the surface texture of the paper is superficial, being limited only to the surface layers, even under these more rigorous conditions, where some degree of measurable surface erosion was anticipated due to the particulate laden oil.

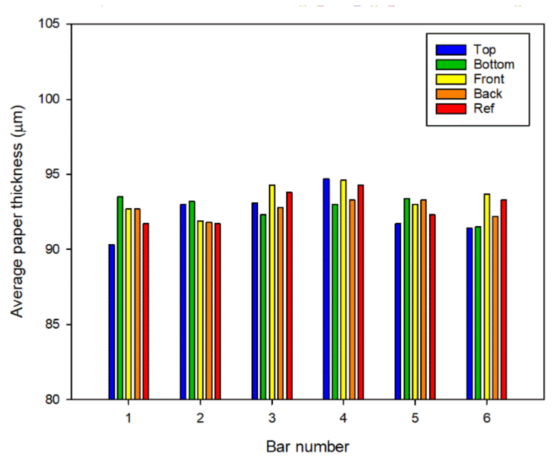

Fig. 10. Results from sample thickness measurement of paper wrapped around the various copper bars. Front is the surface exposed to the oil jet.

IV. Conclusions

To provide samples spanning its full lifecycle within a high voltage transformer, Kraft paper was thermally aged in fan ovens at temperatures of 150, 130 and 110 °C for periods of up to 12 weeks. In addition, UVC irradiation was used to provide an additional sample set with very low values of surface DP which simulate the surface condition of paper in a heavily aged asset. In both cases, the measured DP falls progressively with aging time. For temperatures of 150 and 130 °C the full range of DP values applicable to an aged transformer (1100 to 200) can be accessed, whilst 110 °C was insufficient to achieve this. There was an excellent correlation between the fall in measured DP and the progressive mechanical embrittlement of the paper during aging.

Selected samples were then exposed to oil flows representative of both normal transformer operation and reclamation activities. In 6 h short duration tests, aged samples exposed to high flow rates showed a significant degree of surface roughening (as assessed by optical microscopy) but no measurable erosion (as assessed by measurements of sample thickness) in agreement with our earlier investigations. Further tests performed on severely aged paper under repeated temperature/flow cycling consistent with reclamation activities, showed similarly disrupted textures but again no measurable erosion. The key finding of this work was then verified in a geometry mimicking part of a high voltage transformer winding.

As far as we have been able to reasonably determine using our combination of laboratory aged transformer paper and particulate laden aged mineral oil, normal reclamation activities are unlikely to cause erosion of the paper despite a degree of obvious surface roughening. This is reassuring from the point of view of network operators wishing to reclaim aged assets. However, other potential sources of mechanical damage, such as the electromechanical forces inherent to normal plant operation, cannot be ruled out.

An outstanding concern is posed by lapped paper samples where, due to the tensile stresses imposed on the paper by the winding process, subsequent aging (or drying during reclamation) could cause the paper to fracture and become detached from the windings. A study of the aging behavior of such samples could therefore prove beneficial. Further suggestions would be to carry out validation studies using other oil/paper combinations, perhaps quantify the surface roughness by using a profilometer, measure the DP both before and after exposure to oil flow and determine whether flow-induced changes in paper morphology can affect static electrification.

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