PORTABLE FIBER-BASED FLUORESCENCE SENSOR FOR ONLINE ASSESSMENT OF TRANSFORMER OIL AGEING

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ABSTRACT

Under smart grid scenario, the penetration of electric vehicles would exacerbate the thermal ageing of insulating oil in distribution transformers. This would threaten the reliable and secure operation of distribution transformers and thus requires timely monitoring of oil conditions. In this work, fluorescence spectroscopy is applied to evaluate the ageing status of transformer oil. The fluorescence spectra were measured for the oil samples thermally aged in laboratory. It is found that the ratio of the two peaks in fluorescence spectrum is well in line with traditional ageing parameters, including colour index and total acid number. The preliminary results imply that it is feasible to apply the portable fibre-based fluorescent probe system in the online assessment of the ageing status of transformer oils.

INTRODUCTION

The development of smart grids raises attention to the possibly exacerbated insulation degradation of distribution transformers, because the increasing emergences of electric vehicles would elevate the transient thermal stress and worsen the thermal ageing of transformer oil [1-3]. This would threaten the reliable and secure operation of distribution transformers, increase the complexity of asset management for the large number of distribution transformers and require proper condition monitoring approaches for distribution transformers.

Fluorescence spectrum is sensitively related to the electronic state of the molecules; therefore, it can indirectly indicate the molecular changes during oil ageing process [4-12]. Recent developments in semiconductor diode sources bring down the cost of laser diodes and avail the deployment of cheap and portable fluorescence spectrum instrument [10-12].

This work applies fluorescence spectroscopy and fingerprinting to assess the ageing status of transformer oil, as a part of the goal towards the development of a reliable, cost-effective and field-deployable oil condition monitor for transformers. The fluorescence spectra of the transformer oil samples were measured after the samples were thermally aged in laboratory. It is found that the fluorescence spectrum characteristics are well correlated with traditional ageing parameters, including colour index and total acid number, which makes it feasible to apply this portable fibre-based fluorescent probe system for the ageing assessment of transformer oils.

EXPERIMENTAL

Laboratory Thermal Ageing Test

Nynas 10GBN, a naturally inhibited mineral oil, was subjected to the laboratory thermal ageing experiment which is a widely used approach to estimate the loss of life of the insulation. The samples were aged in an air circulating oven at 115°C. In order to investigate the catalytic effects of copper, copper strips were added into some sample vials (to give a surface area of 9.6 cm^2 per 500 ml) before the ageing experiment was conducted. To study the oxidation effect on thermal ageing, some sample vials were sealed by caps and the rest were left open. Separate 500 ml samples were aged for each specified ageing time.

Colour and Total Acid Number Measurement

After the ageing experiment finished, Lovibond PFX 880 Tintometer was used to measure the colour index according to ASTM D1500 scale [13]. The cuvette for colour index measurement has a 33 mm light path. In addition, Metrohm 848 Titrino plus was used to measure the total acid number of the samples. It was determined by titration of 5 g oil sample with potassium hydroxide (KOH) solution.

Fluorescence Measurement

The hardware of the fluorescence spectrum instrument is shown in Figure 1. The 5 mW GaN based laser diode generates an excitation light with the wavelength of 404 nm. The fibreoptic is connected to the laser diode to transmit the light. It consists of a bundle of seven fibre strands: six 400 µm illumination fibres surrounding one 400 µm reading fibre. The spectrometer measures the intensities of fluorescent light at different wavelengths and transmits the data to the computer.

Disposable cuvettes are used for the measurement in case of contaminations between tests. The cuvettes are made from polystyrene and have a dimension of 10 mm×10 mm×45 mm. To represent the in-situ conditions, the tip of fibreoptic was immersed into the oil samples.

In preliminary tests, influences of moisture, particle and temperature on spectrum were investigated. It was found that added moisture (up to 50 ppm), cellulose and copper particles (up to 150000 particles with size larger than 5 µm per 100 ml) and temperature (up to 80°C) did not change the shape of the spectrum. The spectrum shape is only sensitive to the oil ageing status.

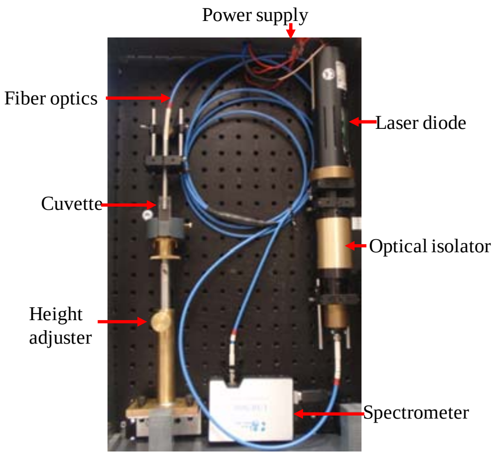
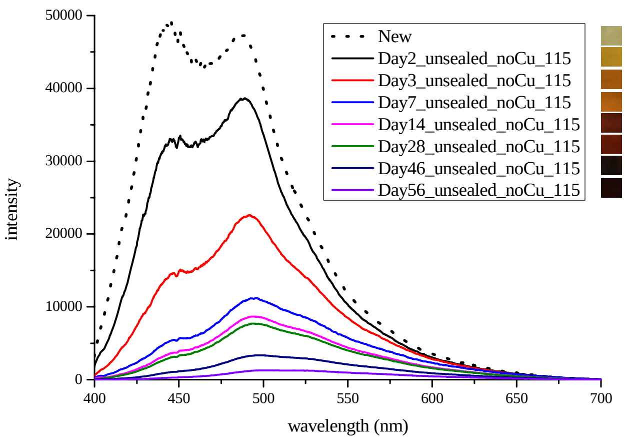


Figure 1 Fluorescence spectrum instrument

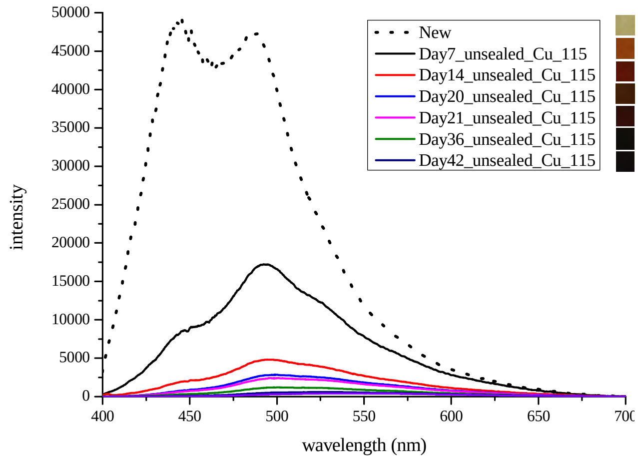
Before fluorescence spectrum measurement, the cuvette with oil sample was vacuumed for 1 minute to remove the bubbles introduced in the sample injection which might influence the spectrum. Since the sensor tip was immersed into the sample, to prevent contamination to the oil sample, the sensor tip was carefully cleaned with fibreless tissues before each measurement.

FLUORESCENCE SPECTRA OF AGED SAMPLES

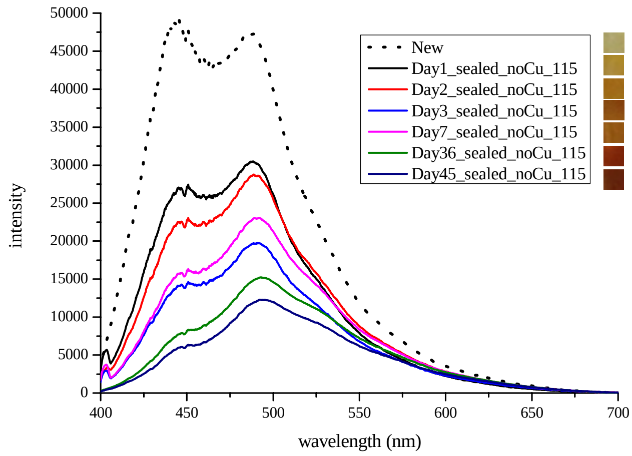
The samples were aged for various days under four conditions, including unsealed ageing without copper, unsealed ageing with copper, sealed ageing without copper and sealed ageing with copper, respectively. After the thermal ageing test, their fluorescence spectra were measured and shown in Figure 2.
As can be seen, the typical spectrum is composed of two peaks at 445 nm and 490 nm respectively for transformer oil samples thermally aged. When thermal ageing occurs, the spectrum intensity reduces significantly with the ageing time; especially the peak at 445 nm gradually disappears.



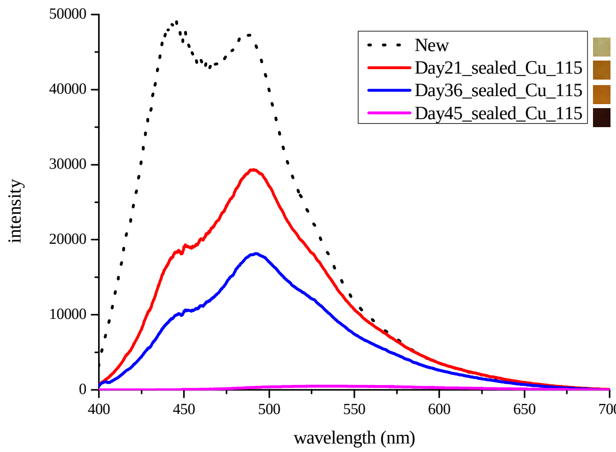
(a) Unsealed ageing without copper at 115°C



(b) Unsealed ageing with copper at 115°C



(c) Sealed ageing without copper at 115°C



(d) Sealed ageing with copper at 115°C

Figure 2 Fluorescence spectra and colour of thermally aged oil samples

The colours for each individual sample are also shown beside the legends in Figure 2 and the colour change is well in line with the spectrum change: the darker the colour, the smaller the spectrum intensity and the more subtle the first peak at 445 nm.
Since during ageing, there is a loss of the first peak at 445

nm when compared to the second peak at 490 nm in the spectrum intensity (I), it is proposed to use this peak ratio (I_{490}/I_{445}) to represent the ageing status of oil samples.
By plotting the spectrum peak ratios of oil samples aged for various periods, the ageing pattern of the samples under various conditions are shown in Figure 3.

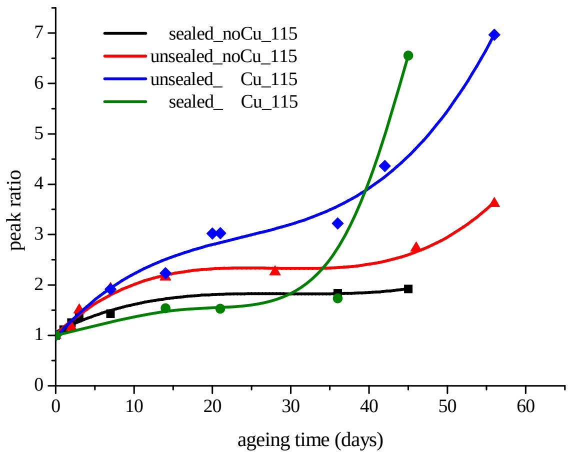


Figure 3 Change of peak ratios with ageing time under various ageing conditions

It can be seen that, for samples aged in sealed condition without copper, the ageing rate is the slowest; for the samples aged in unsealed condition, the samples degrade significantly due to oxidation, with copper as catalyst [14]; for the samples aged with copper, but in sealed condition, the ageing rate is also obvious, which might be attributed to water, because in sealed ageing, water generated from ageing cannot be evaporated and it will further exacerbate the ageing [15].

CORRELATION OF PEAK RATIO WITH COLOR INDEX AND TOTAL ACID NUMBER

The change of peak ratios with ageing time under various ageing conditions is in line with the basic understanding about ageing mechanisms. To further verify the effectiveness of the peak ratio in fluorescence spectrum as an ageing indicator, the peak ratio was also correlated with colour index and total acid number, the two conventional ageing indicators widely used by utilities.
As can be seen in Figure 4, the ASTM colour scale shows a good exponential relationship with the peak ratio of spectrum, with a determination coefficient (R^2) of 0.97. The correlation between peak ratio (PR) and the colour index (CI) can be written as:

$$PR = 0.82 + 0.27 * \exp(0.44 * CI)$$

As shown in Figure 5, the total acid number shows a good linear relationship with the peak ratio of spectrum, with a determination coefficient (R^2) of 0.99. The correlation between peak ratio (PR) and the total acid number (TAN) can be written as:

$$PR = 0.91 + 9.41 * TAN$$

The goodness of fitting of colour index and total acid number with the peak ratio in spectrum denotes that the spectrum characteristic represented by the peak ratio can be used to deduce the colour index and total acid number of the sample.

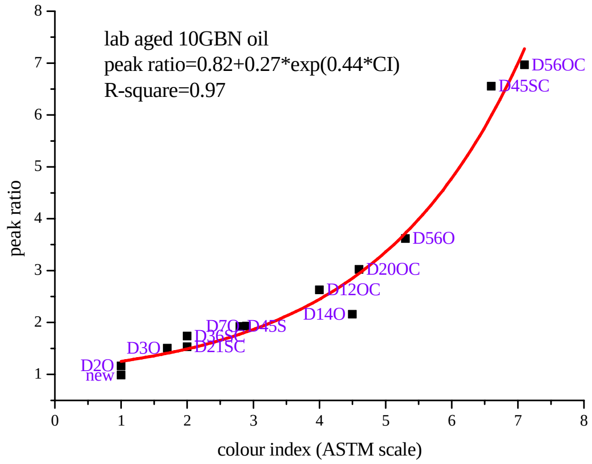


Figure 4 Correlation between peak ratio and colour index (in sample labels, D for day, S for sealed, O for open, C for copper)

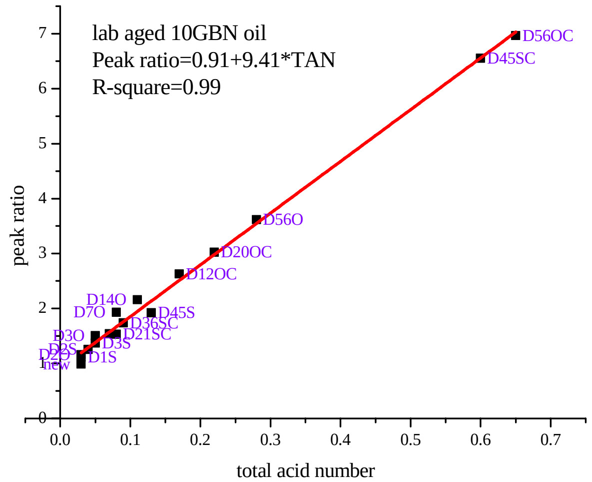


Figure 5 Correlation between peak ratio and total acid number (in sample labels, D for day, S for sealed, O for open, C for copper)

DISCUSSIONS

The good correlation of peak ratio with colour index and total acid number indicates that peak ratio could be an effective ageing indicator.
As specified in IEC 60422 [16] and widely used by utilities, regarding distribution transformers rated up to 72.5 kV, when the total acid number is higher than 0.15 mg KOH/g, the deterioration of oil quality can usually be detected, the oil should be more frequently sampled, and the presence of sediment and sludge should be checked; when the total acid number is above 0.30 mg KOH/g, the abnormal deterioration of oil quality has usually started already, a decision may be required on when to reclaim or replace the oil. Based on the fitted correlation between total acid number and peak ratio of the spectrum, it can be seen that for aged 10GBN, peak ratio of spectrum

larger than 2.3 corresponds to total acid number over 0.15 mg KOH/g, whereas the peak ratio larger than 3.7 corresponds to total acid number higher than 0.30 mg KOH/g.

Due to the different oil properties (original colour, inhibited or not, etc), oils might behave differently during ageing process. Consequently, the numerical constants in the correlation equations of spectrum peak ratios with colour index and total acid number might be different. However, these constants could be deduced for each type of oil using laboratory accelerated ageing tests. In this way, a fluorescence spectroscopy fingerprinting library can be established and used for the ageing assessment for various types of transformer oils.

CONCLUSIONS

In this work, the fluorescence spectroscopy using a low-cost 404 nm fibre-based GaN semiconductor laser sensor was applied to assess the ageing status of transformer oil thermally aged in laboratory.

It is found that the peak ratio (ratio of intensity at 490 nm and 445 nm) of the fluorescence spectrum has good quantitative correlations with traditional ageing indicators, such as colour index and total acid number, which indicates that fluorescence spectrum measurement could be an effective approach for oil ageing assessment. It can supplement the traditional colour index and total acid number measurements, with an advantage of lower cost.

Our preliminary research on laboratory accelerated aged samples implies that, it might be feasible to develop a low-cost and field-deployable fluorescence sensor to evaluate the transformer oil ageing status online.

Acknowledgments

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