Transformer Working Condition Assessment using Laser Raman Spectroscopy

Toshihiro Somekawa[1], Makoto Kasaoka[2], Fumio Kawachi[2],
Yoshitomo Nagano[2], Masayuki Fujita[1,3] and Yasukazu Izawa[1,3]
[1]*Institute for Laser Technology, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan*
[2]*Kanden Engineering Corporation, 3-1-176 Fukuzaki, Minato-ku, Osaka 552-0013, Japan*
[3]*Institute of Laser Engineering, Osaka University, 2-6 Yamadaoka, Suita, Osaka 565-0871, Japan*

Keywords: Raman Spectroscopy, Transformer, C_2H_2, Furfural.

Abstract: Analyses of dissolved gas and furfural in the insulating oil are a very efficient tool for assessing the working conditions of transformer. We propose the in-situ transformer health diagnosis without the need for oil sampling by measuring the Raman signals from C_2H_2 and furfural concentrations present in transformer oils. Raman signals in oil at ~1972 cm^{-1} and ~1705 cm^{-1} originating from C_2H_2 and furfural, respectively, were detected. The results show that laser Raman spectroscopy is a useful alternative method to diagnose the transformer faults.

1 INTRODUCTION

Transformers are important components in any power system and their condition monitoring is essential for ensuring reliable operation of the system. In general, power transformer coils are insulated with a cellulose paper and immersed in mineral oil. Under the normal operating conditions, insulating mineral oils in the transformers include small amounts of gases, but failure of the transformer is known to be preceded by significant evolution of hydrogen(H_2), carbon monoxide(CO), carbon dioxide(CO_2), methane(CH_4), ethane(C_2H_6), ethylene(C_2H_4), and acetylene(C_2H_2) gases caused by corona discharges, overheating, and arcing. Therefore, a dissolved gas analysis (DGA) of the insulating oils has become the most widely used method for investigating incipient faults in transformers (Duval, 1989). Dissolved gases extracted from oil aliquots due to pressure reduction or substitution by inert gases are measured by gas chromatography. In addition, it is known that furfural in oil comes only from the decomposition of insulation paper. So the furfural content in insulation oil is an important indicator for assessing the degradation of insulating paper in transformer (Morais et al., 1999). Furfural concentration in oil was generally extracted by methanol and measured by high performance liquid chromatograpy. These methods usually offer sensitive detection limits at ppm levels that are suitable for monitoring the transformer conditions, but require time consuming preprocessing steps and include risks of sample contamination during sampling.

We recently reported detections of C_2H_2 dissolved in the insulation oil using laser Raman spectroscopy technique (Somekawa et al., 2013). C_2H_2 is mainly produced at very high temperatures that occur in presence of arcing. C_2H_2 is not detected in transformers during normal operation, but concentrations as high as 1% are detected in presence of huge arcing (Duval and dePablo, 2001). Therefore, C_2H_2 is introduced as an effective indicator. Our approach does not require gas separation in oils and the gas content in the insulating oil is directly measured by irradiating laser. Based on this technique, on-line and in-situ detection of dissolved gases and byproduct materials can be adapted for diagnosis of transformer faults.

In this paper, we demonstrate that C_2H_2 and furfural in insulating oils can be directly detected by Raman spectroscopy. We found that Raman signals of C_2H_2 (~1972 cm^{-1}) and furfural (~1705 cm^{-1}) can be used for monitoring the transformer condition with no interfering peaks overlapping from the insulating oil. Hence, Raman spectroscopy could be a useful technique for in-situ transformer health diagnosis without the need for oil sampling.

Somekawa T., Kasaoka M., Kawachi F., Nagano Y., Fujita M. and Izawa Y..
Transformer Working Condition Assessment using Laser Raman Spectroscopy.
DOI: 10.5220/0004710800210025
In *Proceedings of 2nd International Conference on Photonics, Optics and Laser Technology* (PHOTOPTICS-2014), pages 21-25
ISBN: 978-989-758-008-6

2 EXPERIMENTAL

2.1 Raman Spectroscopy

Figure 1 shows the schematic diagram of Raman spectroscopy. The laser was a standard Q-switched Nd:YAG laser (Continuum, Surelite: 10 ns pulse-width with 100 mJ pulse energy at 10 Hz repetition rate) operating at its second harmonic wavelength of 532 nm. A non-focused laser beam having about 8 mm diameter was used to avoid laser induced damage of oil sample. The Raman signals from samples are collected using an achromatic lens at an angle of 25° from the forward direction of the laser beam. This design provides a longer optical path length than a conventional detection geometry at 90°, offering an order of magnitude increase in Raman scattering intensity. After passing through the edge and notch filters at 532 nm, the Raman signal is coupled into an optical fiber bundle by using an achromatic lens. The collected Raman signal is dispersed by a spectrometer (Acton, SpectraPro-2300i) with an entrance slit width set to 15 μm and detected with a liquid nitrogen-cooled charge-coupled device (CCD) camera (Princeton Instruments, SPEC-10). The exposure time was 90 ms. Accumulation numbers of C_2H_2 and furfural measurements were 3000 and 500, respectively. Higher accumulation number in the C_2H_2 detection was required to reduce the random noise in Raman spectra and improve the S/N ratio. The spectral resolution of this system was estimated to be about 5 cm^{-1}.

2.2 Sample Preparation

The insulating oil used in this work was a mixture of naphthenic(41.6%), paraffinic(50.0%), and aromatic(8.4%) oils. The used insulating oil samples were optically clear in visible region. The insulating oils were stored in glass bottles with diameters of 3 cm. We confirmed that the glass bottles had no effect on Raman spectra. After complete degassing in vacuum for 4 hours, high-purity C_2H_2 gas (more than 99%) was introduced via a gastight syringe. The C_2H_2 concentrations of the samples under the investigation were measured by the gas chromatography and had 1.9%, 5.7%, and 10% concentrations, respectively.

Furfural is only slightly soluble in this oil. Therefore, toluene solvent is added to oil. The concentration of toluene in oil was constant at approximately 9% for quantitative analysis. Furfural used in this experiment becomes yellow on exposure to air and light, but the spectrum obtained using 532 nm excitation is not dominated by fluorescence.

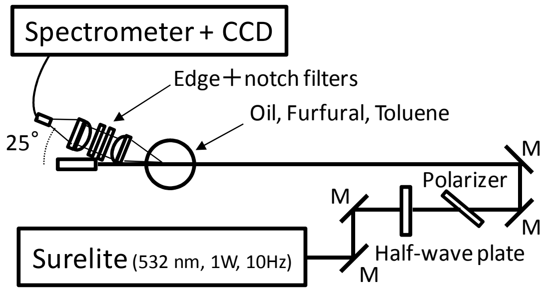

Figure 1: Schematic diagram of the experimental setup.

3 RESULTS AND DISCUSSION

3.1 Raman Spectrum of Oil

Figure 2(a) shows the Raman spectra of oil. In short and long edges of the spectrum, it exhibits numerous features that are specific to complex oil structures (Somekawa et al., 2013), however, it has no large Raman spectral features and relatively low background baseline between 1700 to 2500 cm^{-1} range. The large peak centered at 1450 cm^{-1} corresponds to CH_3-CH_2 bending mode, and the set of peaks at 1302 and 1350 cm^{-1} corresponds to paraffin C-H twisting modes. The peak at 1610 cm^{-1} is due to an aromatic C=C stretching mode. The band at 2725 cm^{-1} can be assigned to the C-H stretching mode. In higher wavenumber side not shown here, the Raman spectrum of oil shows only C-H stretching mode around 3000 cm^{-1}, but no signals in the region between 3100 and 4200 cm^{-1}. Figures 2(b) and 2(c) show the Raman spectra of furfural and toluene, respectively, as discussed below.

3.2 Raman Spectrum of C_2H_2 Dissolved in Oil

Figure 3 shows the spectra of C_2H_2 gas at different concentrations dissolved in the insulation oil. These Raman spectra were normalized at ~2191 cm^{-1} Raman signal intensity peaks. Weak Raman signals were detected at 2191 cm^{-1}, which were assigned to the oil-derived Raman signal since its Raman peak intensity remained almost unchanged as the C_2H_2 concentration increased in the oil. On the other hand, Raman peak intensity of relatively sharp line at ~1972 cm^{-1} increased linearly versus increasing C_2H_2 concentration. We assign the peak around 1972

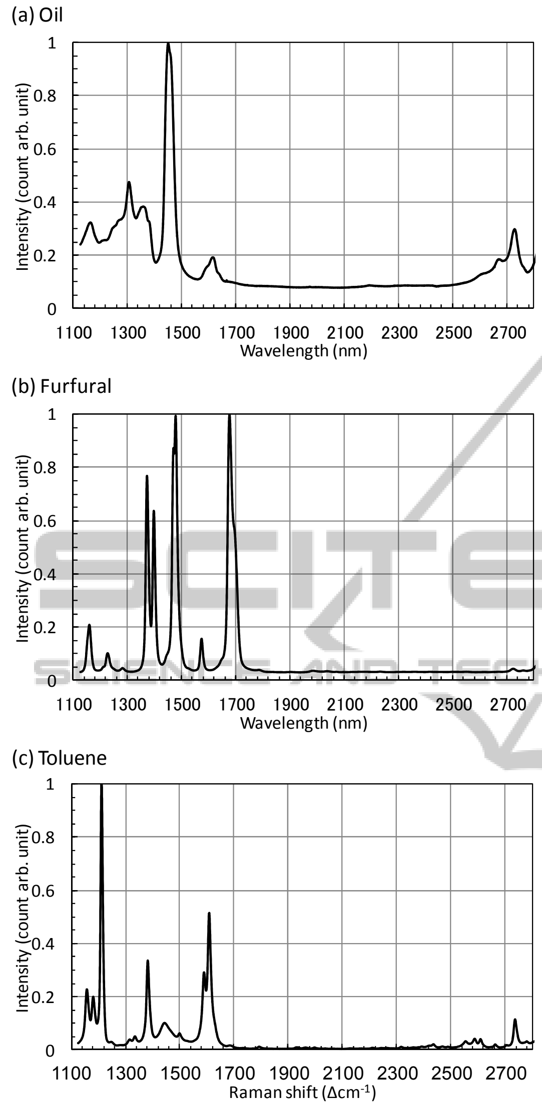

Figure 2: Raman spectra of (a) oil, (b) furfural and (c) toluene.

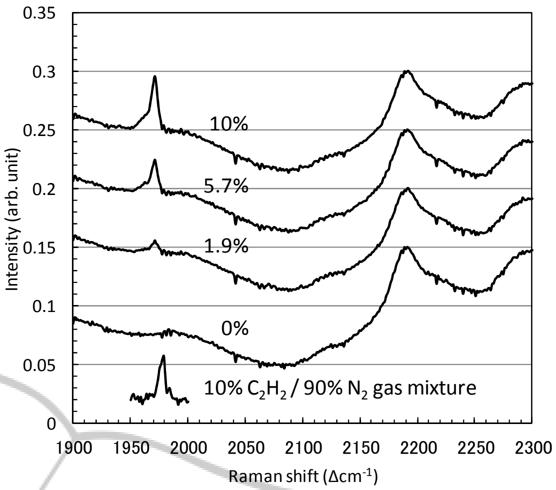

Figure 3: Raman spectra of C_2H_2 gas at different concentrations dissolved in the insulation oil.

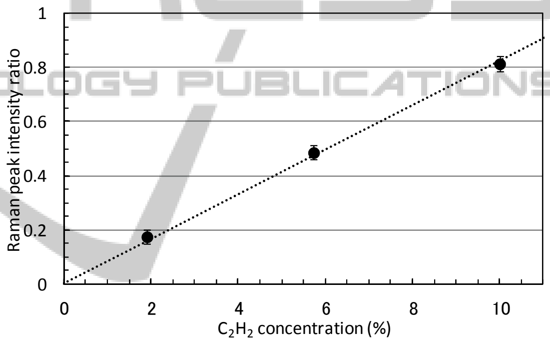

Figure 4: Raman peak intensity ratio ($I_{1972cm-1}/I_{2191cm-1}$) as a function of dissolved C_2H_2 concentration in oil.

cm^{-1} to the C≡C stretching mode of C_2H_2 (Fast and Welsh, 1972). We conclude from Fig. 3 that the Raman band of C_2H_2 located at ~1972 cm^{-1} can be used for monitoring the C_2H_2 dissolved in the insulation oils. In Fig. 3, Raman spectrum of 10% C_2H_2 and 90% N_2 gas mixture is also presented. When C_2H_2 is dissolved in oil, the gas phase band position at ~1979 cm^{-1} is shifted to ~1972 cm^{-1} in oil. This shift could be attributed to the variation of vibration modes in oils (Somekawa et al., 2013).

Quantitative analysis in Raman spectroscopy was performed with a band intensity ratio. This is because the Raman scattering intensity is a weak signal and the reproducibility of a Raman spectrum is degraded due to the variation in the excitation laser intensity and changes in the sample matrix. The oil-derived Raman signals at ~2191 cm^{-1} were used for these analyses. Figure 4 shows Raman peak intensity ratios, $I_{1972cm-1}/I_{2191cm-1}$, as a function of C_2H_2 concentration. The error bars were evaluated using the standard deviation of 10 consecutive spectra. The slope of the linear fit is 0.0825. Therefore, the C_2H_2 concentration is determined by this slop and the Raman peak intensity ratio. Also, we estimated the detection limit of the present system to be $3\sigma_{C2H2}$~0.37%, where σ_{C2H2} is the standard deviation of the Raman spectra from C_2H_2 free oil sample (0%) in 1952-1977 cm^{-1} spectral range. Thus, the high C_2H_2 concentrations (~1%) observed in actual insulating oils are detectable with current Raman system. On the other hand, the detection limits could be improved by using longer path length oil sample, higher average power CW laser, and more sensitive CCD detector.

3.3 Raman Spectrum of Furfural in Oil

Figure 2 shows the Raman spectra of (b) furfural and (c) toluene. The furfural Raman spectrum shows a H-C-C/O bending mode at 1372 cm^{-1}, C-C stretching mode at 1398 cm^{-1}, C=C stretching modes at 1478 and 1573 cm^{-1}, C=O stretching modes at 1675-1705 cm^{-1}(Kim et al., 2011). As shown in Fig. 2(c), the measured Raman spectrum of toluene includes no spectral interferences caused by Raman band overlap over ~1600 cm^{-1}. Detailed toluene mode assignments can be found elsewhere (Hameka and Jensen, 1996).

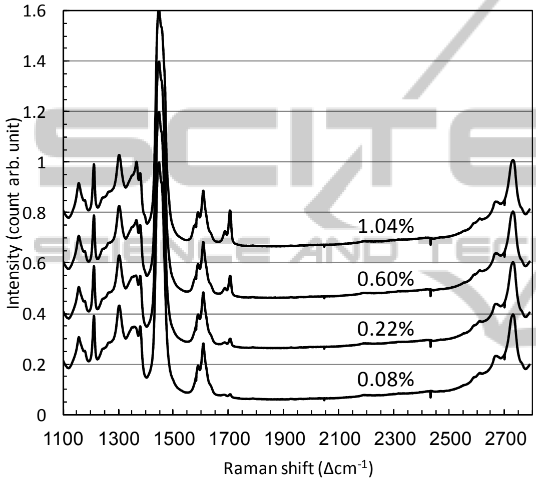

Figure 5: Raman spectra of furfural at different concentrations in oil in the presence of toluene (~9%) as a solvent.

The furfural spectrum clearly shows an additional C=O stretching mode at 1675-1705 cm^{-1}, which is not found in oil. Thus, we can easily distinguish furfural from oil using this Raman band. Figure 5 shows Raman spectra of furfural at different concentrations in oil, in the presence of toluene (~9%) as a solvent. Raman peak intensity at ~1705 cm^{-1} increased linearly versus increasing furfural concentration. The spectral shape differences between Fig. 2(b) and Fig. 5 can be observed at 1675-1705 cm^{-1}, which may be due to strong solvent interference (Allen and Bernstein, 1955).

Figure 6 shows Raman peak intensity ratios, $I_{1705cm-1}/I_{1608cm-1}$, as a function of furfural concentration. The Raman ratio at 1705 cm^{-1} shows a linear dependence on the furfural concentration in contrast to the non-linear relationship between the Raman ratio at 1687 cm^{-1} and furfural concentration. In this study, as a furfural-concentration-invariant signal, we choose the Raman peak of oil and toluene mixture at 1608 cm^{-1}. The error bars were evaluated using the standard deviation of 5 consecutive spectra and were hidden in the plot symbols. These ratios can be reasonably well fitted by a line with a slope of 0.643. We estimated also the detection limit of the present system to be $3\sigma_F$~65 ppm, where σ_F is the standard deviation of the Raman spectra from 0.08% furfural sample between 1720 to 1750 cm^{-1} range. However, the permissible concentrations of furfural in oil are 1.5 and 15 ppm at caution and danger levels, respectively (Okabe et al., 2013). Therefore, further development of the measurement system is needed to improve sensitivity.

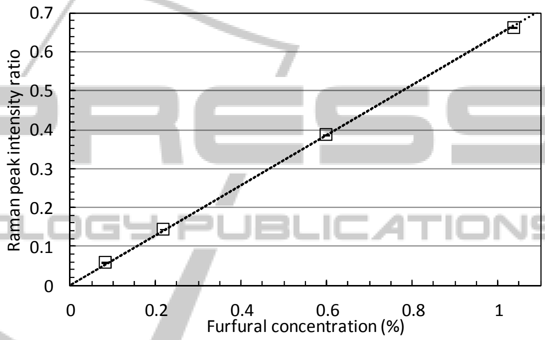

Figure 6: Raman peak intensity ratio ($I_{1705cm-1}/I_{1608cm-1}$) as a function of furfural concentration in oil.

4 CONCLUSIONS

We demonstrated in-situ application of Raman spectroscopy for detection of C_2H_2 and furfural in the insulating oil to diagnose the transformer health. Our method also has the advantage of simplicity, time savings and non-requirement of sample preprocessing. In addition, the Raman spectroscopy could simultaneously monitor multi-trace gases and byproduct materials to get relevant information about the transformer condition.

In future research, sensitivity improvements of our Raman spectroscopy system will be performed. We believe it can be generally applied for assessing the transformer conditions.

REFERENCES

Allen, G., Bernstein, H. J., 1955. Internal Rotation VII. The infrared and Raman spectra of furfural. In *Can. J. Chem.*, 33, 1055-1061.

Duval, M., 1989. Dissolved Gas Analysis: It Can Save Your Transformer. In *IEEE Electr. Insul. Mag.*, 5, 22-27.

Duval, M., dePable, A., 2001. Interpretation of Gas-In-Oil Analysis Using New IEC Publication 60599 and IEC TC 10 Databases. In *IEEE Electr. Insul. Mag.*, 17, 31-41.

Fast, H., Welsh, H. L., 1972. High-Resolution Raman Spectra of Acetylene, Acetylene-d1, and Acetylene-d2. In *J. Mol. Spectrosc.*, 41, 203-221.

Hameka, H. F., Jensen, J. O., 1996. Theoretical studies of the methyl rotational barrier in toluene. In *J. Mol. Struct. (Theochem)*, 362, 325-330.

Kim, T., Assary, R. S., Curtiss, L. A., Marshall, C. L., Stair, P. C., 2011. Vibrational properties of levulinic acid and furan derivatives: Raman spectroscopy and theoretical calculations. In *J. Raman Spectrosc.*, 42, 2069-2076.

Morais, R. M., Mannheimer, W. A., Carballeira, M., Noualhaguet, J. C., 1999. Furfural Analysis for Assessing Degradation of Thermally Upgraded Papers in Transformer Insulation. In *IEEE Trans. Dielectr. Electr*. Insul., 6, 159-163.

Okabe, S., Ueta, G., Tsuboi, T., 2013. Investigation of Aging Degradation Status of Insulating Elements in Oil-immersed Transformer and its Diagnostic Method Based on Field Measurement Data. In *IEEE Trans. Dielectr. Insul.*, 20, 346-355.

Somekawa, T., Kasaoka, M., Kawachi, F., Nagano, Y., Fujita, M., Izawa Y., 2013. Analysis of dissolved C2H2 in transformer oils using laser Raman spectroscopy. In *Opt. Lett.*, 38, 1086-1088.