Advanced Materials Research *Online: 2012-12-13*
ISSN: 1662-8985, Vols. 614-615, pp 1163-1167
doi:10.4028/www.scientific.net/AMR.614-615.1163

Temperature Dependence of On-line DGA Results for Transformers through Membrane Extraction

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Keywords: Transformer, dissolved gas analysis, on-line monitoring, extraction membrane, temperature coefficient

Abstract. Concentration detection of gases dissolved in transformer insulation oil is an effective method to diagnose incipient fault in electrical equipment. The permeation process of gases dissolved in transformer oil through extraction membrane is studied. Temperature dependence with accuracy of on-line DGA results through gases extraction with polymer membrane is analysed. An algorithm which includes temperature coefficient which can improve the accuracy of DGA results is proposed. An on-line DGA system with Teflon membrane and electrochemical gas sensors is constructed; while the results are adjust by temperature coefficient. Compared with GC results in the laboratory, the accuracy of the on-line DGA results has been improved.

Introduction

Certain electrical and thermal phenomena within transformers produce various gases (H_2, CH_4, C_2H_2, C_2H_4, C_2H_6, CO, CO_2) that dissolve in transformer insulation oil [1]. Hence, for many years now, dissolved gas analysis (DGA) has been widely accepted to forecast incipient faults in oil-filled transformers. Nowadays, the quantification of fault gases is usually done by gas chromatography (GC) in the laboratories, which is a well-known diagnostic technique used to quantify the ratios of the fault gases. Nevertheless, there are many disadvantages of off-line DGA in the laboratories which lead to the inaccuracy in the DGA results, so considerable interest in installing on-line DGA systems with polymer membrane which can extract dissolved gas in the field increased.

Nowadays, on-line monitoring devices with membranes have been installed in many transformers in China [2]. However the accuracy of on-line DGA results acquired by those on-line equipment needs to be increased, and there is no coherent standard for on-line DGA results [3].As on-line DGA results can be influenced by many factors in which the temperature influence must be considered, for the reason that on-line system is running for the filed tests [4,5]. In this paper the influence of oil temperature and ambient temperature on the on-line DGA results is discussed, and the temperature coefficient is proposed to adjust the on-line DGA results.

Theories

Henry's law – Fickian diffusion model is normally used to describe the permeation of a pure gas in membranes. The concentrations of gases detected by gas sensors need to be converted into the concentrations of gases dissolved in transformer oil. The relationship between those two concentrations is illustrated as:

$$C_g=(9.87k_iC_0-C_{g0})[1-\exp(-1.013\times10^5\times P_iSt/dV)]+C_{g0}. \quad (1)$$

Where C_g is the concentration of gases in the gas cell, C_{g0} is the concentration of gas before the permeation starts, as when t=0, C_{g0}=0 and C_o is the concentration of gases dissolved in the oil in fact. And k_i is coefficient which shows the dissolution of gases in oil, P_i the permeability coefficient of gas i, S the total membrane available for permeation, d the thickness of the membrane wall, t the time of permeation, V the volume of internal cavity. P_i can be calculated from the relation:

$$P_i=bdV/(1.013\times10^5\times S). \tag{2}$$

Where b is corresponding to the steady-state transmission rates of the penetrant, and has been tested in former literature. Eq. 1 and 2 can be used to compute the concentration of gases dissolved in the oil, and then the concentrations of gases dissolved in oil are acquired. The transport properties of gases for a plane membrane selected in this work were determined by a nonlinear least-square regression of the exponential growth function [6]:

$$C_i=C_i^{\max}[1-\exp(-bt)]. \tag{3}$$

Where, C_i is the concentration of gas i, $C_i^{\max}$ is the equilibrium concentration of gas i, b is the slope of the portion of the curve corresponding to the steady-state permeation rate, and t is the time.

For gas i at time t_n, the detected gas concentration is C_{in}, the equilibrium concentration is $C_{in}^{\max}$; and at the time $t_{n\text{-}1}$, the gas concentration is $C_{in\text{-}1}$, the equilibrium concentration is $C_{in\text{-}1}^{\max}$. If $C_{in}^{\max}$ is acquired at small intervals, t_n - $t_{n\text{-}1}$=Δt, and assuming that the slope b does not change from time t_n to time $t_{n\text{-}1}$ for C_n and $C_{n\text{-}1}$, then from Eq. 1 and 3 the following relationship is obtained:

$$C_i^{\max}=[C_{in}\text{-}\exp(-b\Delta t)\,C_{in\text{-}1}]/[1\text{-}\exp(-b\Delta t)]. \tag{4}$$

If it is also assumed that the time interval between measurements is very small, then the slope b does not change measurably from $t_{n\text{-}1}$ to t_{n+1}, then the following equations can be derived from Eq. 4:

$$\ln[(C_i^{\max} - C_{in})/(C_i^{\max} - C_{in\text{-}1})]= \ln[(C_i^{\max} - C_{in+1})/(C_i^{\max} - C_{in})]= b\Delta t. \tag{5}$$
$$C_i^{\max}=(C_{in\text{-}1}C_{in+1}\text{-}\ C_{in}^2)/(C_{in\text{-}1}+C_{in+1}\text{-}2\,C_{in}). \tag{6}$$

where, three concentrations $C_{in\text{-}1}$, C_{in} and C_{in+1} of the dissolved gas i are used for the estimation of the equilibrium concentration $C_i^{\max}$ and where the slope of the permeation rate b is not involved in the estimation.

If heat conduction is not in the membrane through the permeation progress, the dependence of permeability coefficient and temperature can be described as [7]:

$$P_i=P_0\exp[-E_p/(RT)]. \tag{7}$$

where, P_0 is a temperature-independent pre-exponential factor, E_p the apparent activation energy for permeation , R the gas constant and T the test temperature in K. When the temperature of gaseous phase changes from -20℃ to 60℃ and the membrane is Teflon, gas is CO; the change of P_i is demonstrated in Table1.

Table 1 Temperature dependant of permeability coefficient

T/℃	-20℃	0℃	10℃	23℃	60℃
P_i/CO	$0.471P_0$	P_0	$1.295P_0$	$1.884P_0$	$4.662P_0$

From Table.1, the change of P_i is obvious, and these are dependence of temperature on equilibrium. Thus, when the temperature is T_i, the permeation coefficient is P_i,

$$\ln(P_2/P_1) = \ln(b_2/b_1) = [E_p(T_2-T_1)]/(RT_2T_1). \tag{8}$$

Let temperature coefficient $\beta_P = b_2/b_1 = P_1/P_2$, and $C_i^{max\prime}$ is the equilibrium concentration after the influence of temperature change is eliminated, and then Eq. 5 can be changed as:

$$[(C_n-C_n^{max})/(C_{n-1}-C_n^{max})]^{\beta p} = (C_n-C_n^{max\prime})/(C_{n-1}-C_n^{max\prime}). \tag{9}$$

Where $C_i^{max\prime}$ is the equilibrium concentration of gases dissolved in oil phase, after the adjustment by the temperature coefficient β_P, the influence of temperature on on-line DGA results can be eliminated.

Experimental and Results

The whole system has been mounted to a 500kV transformer in Shen Yang, Liaoning Province, China. Initially, permeation tests of Teflon plane membranes to CO and H_2 were determined in the laboratory at 40°C in a gas cell of diameter 36 mm and volume 17cm^3. These tests were done to establish the permeation transport properties of the membrane and the gas cell, or b which is the slope of the portion of the curve corresponding to the steady-state permeation rate and t_{99}, which is the time taken by each gas to reach 99% of its equilibrium concentration[8].

After sampling, the time for the membranes to re-equilibrate each species needs to be determined. This time was estimated from (1) by calculating the time taken by each gas to reach 99% of its equilibrium concentration (t_{99}) by Eq. 1.

$$C_i/C_i^{max} = 1-\exp(-bt_{99}) = 0.99. \tag{10}$$

In this paper, we take CO as an example, from which the equilibrium time t_{99} is 184.3 hours. From the previous section, for gas i at time t_n, the detected gas concentration is C_{in}, and if the sampling interval is very short, the slope b does not change from time t_n to time t_{n-1} for C_n and C_{n-1}. Therefore, the equilibrium concentration C_{in}^{max} can be calculated from Eq. 4. As can be seen in Figure 1, the first 60 data points show the permeation rate of CO and the equilibrium concentration was determined to be 171 ppm while during the same interval, the gas chromatograph result was 162 ppm. However, at t_{99} = 184.3 hours as determined in the laboratory, the detected concentration of CO reached only 120 ppm. The time taken for CO to reach 99% of its equilibrium concentration is 528 hours, which is much too long for the technique to be useful in the field.

To shorten the time to establish the equilibrium concentration, Eq. 4 is used to calculate the equilibrium concentration, and C_{CO}^{max}. For example, from Figure 1, C_{CO} = 0.4 ppm at t_1=12 hours, and C_{CO} = 62.0 ppm at t_2 = 24 hours, and as t_1- t_2=12 hours, and b_{CO} =0.025 hour^{-1}, then from Eq. 4, C_{CO}^{max} = 158.45 ppm. This calculation was done for each data point in Figure 1. Figure 2 shows the results of C_{CO}^{max} calculated using Eq.4 and using the data from Figure 1. , the average equilibrium concentration of CO within t_{99} = 184.3 hours is 159.9 ppm.

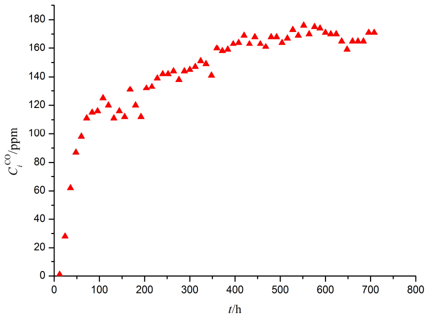

Figure1. Detection data of CO concentration

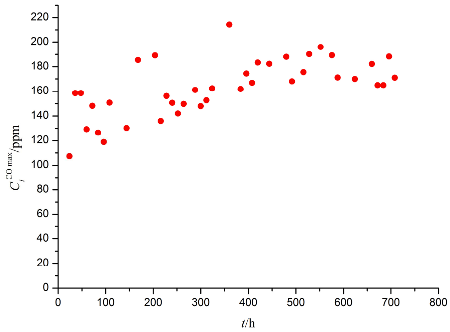

Figure2. Data of calculated C_i^{max} for CO

However, in the field measurements, the oil temperature changes slightly when CO is detected, fluctuating around 38°C which results in a change in b, so the influence of a change in temperature on the permeation must be quantified. As in Eq. 4, 7 and 8, the oil temperature can influence the equilibrium concentration of gases. The temperature of oil is detected in every 20 minutes, the fluctuation of oil temperature can not be ignored, and the temperature coefficient β_P and Eq. 9 is used to calculate the equilibrium concentration of CO dissolved in the oil. The results are shown in Fig. 3 and Table 2. . Fig. 3 demonstrated that the time through which the equilibrium concentration can be reached is shortened obviously, and compared with off-line DGA results the accuracy of on-line DGA is improved.

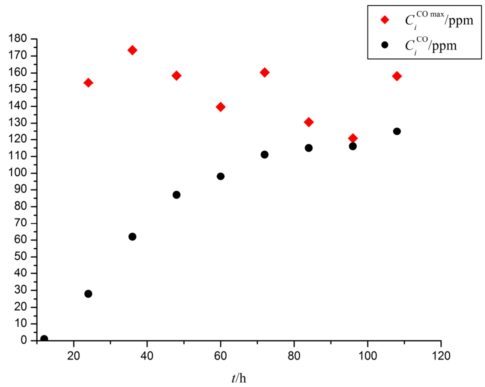

Figure3. Comparison of calculated C_i^{max} and original data for CO

Table 2 Comparison of on and off line DGA results for CO

Off-line DGA[ppm]	On-line DGA[ppm]	On-line DGA(withEq.6)[ppm]	On-line DGA(withEq.9)[ppm]
162	28	107.44	154.15
162	62	158.47	173.36
162	87	158.45	158.45
165	111	148.15	160.29
165	125	150.72	158.13
165	144	161.14	161.14
167	151	162.43	162.43

Permeation of dissolved gases in membranes is a dynamic process, and therefore, the equilibrium state is not constant but actually fluctuates. So, the concentrations of gas need to be re-estimated with many factors. Using Eq. 6 and Eq. 9 can get the equilibrium concentration and eliminate the influence of oil temperature instantaneously. This method has the advantage of allowing the estimation of the concentrations of gases dissolved in a time that is very short when compared with time for equilibrium and without considering the specific running state of transformer or processing technique of the membrane.

Conclusions

Accuracy of on-line DGA results can be affected by certain circumstance in the filed tests, where temperature, no matter oil temperature or ambient temperature, is a major influencing factor. Through the permeation of gases dissolved in transformer oil, temperature affects not only the time that the permeation reaches equilibrium, but also the equilibrium concentration of the gases in the gaseous phase. Therefore temperature coefficient is proposed to adjust the on-line DGA results. The filed test shows the method with temperature coefficient can improve the accuracy and the reliability of on-line monitoring systems. The results obtained by the method suggest that the on-line monitoring systems with membranes have potential for further development in the future.

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