The Oil - Moisture Diagnostic Problem of Aged Transformers

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1. Introduction

The present indirect diagnostic method of taking an oil sample for the estimation of water contamination of power transformers is based on the parallel measurement of two values - water content in the oil by the Karl Fisher method $C_{w,KF}$ (ppm) and the average temperature of the transformer oil cellulose system T(C). This method can sometimes lead to inaccurate, contradictory and quite curious diagnostic results.

An example of a diagnostic discrepancy, is when the aged oil in a transformer is replaced by new oil. Following the oil change, the $C_{w,KF}$ value is always higher in the aged oil compared to the new oil at the same transformer temperature.

This discrepancy is hard to accept and understand.

Let's say, we have a transformer with 10,000 kg oil and 1,000 kg of cellulose. Before and after the oil change the transformer is operated at the same temperature (T= 50C). The water in oil results are ($C_{w,KF}$) 30 ppm in the aged oil and 20 ppm in the new oil.

According to a Nielsen Equilibrium chart ([L2] - Fabre-Pichon Diagram), before the oil change the water content in the cellulose (Cp) is 4.3 %, or 43 kg (1000 x 0.043). However using the same chart, the new oil value gives a water content of 3.2 % or 32 kg of water ? With the aged oil a maximum of (10,000 x 0.000030) 0.3 kg of water will be in the oil, and 0.2kg for the new oil. Why is there a variance of 11kg of water, and how can the water disappear just by changing the oil ?

2. Experimental apparatus

For a simulation of the problem, the experimental apparatus shown in Fig. 1 was used.

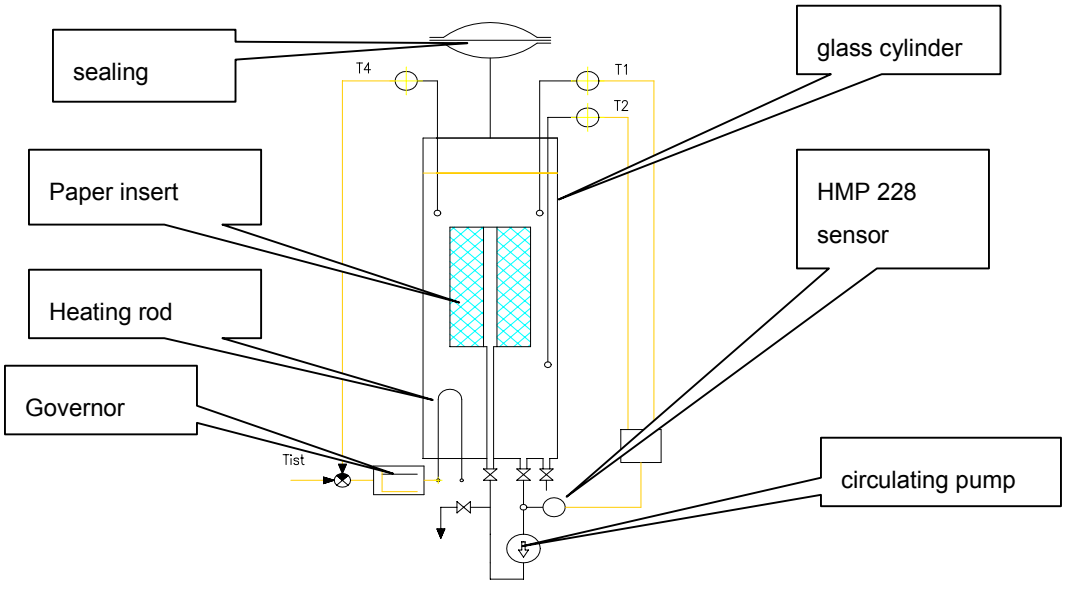

Fig.1 Oil-cellulose moisture equilibrium simulator

The apparatus consists of the glass cylinder with a volume of 30 litres, which is hermetically sealed against the surroundings by the dilatation extension on the upper part. To replicate a typical transformer, 1.5 kg of cellulose was immersed in 20 litres of oil. To reach an equilibrium quickly, electrically heated oil was circulated through the cellulose by a pump. The oil-cellulose system can then be held by the PI-governor at the desired constant temperature level with accuracy + - 0.5 C.
The water content of the oil in the experimental apparatus was measured by two parallel methods, by on-line moisture sensor HMP228 [L3] and by the Aquameter (BAUR RFM 1000 traditional sampling method by). All temperatures are measured by Ni 1000 sensors.
For the experiment, measurements were carried out on both **new** inhibited napthenic transformer oil with the neutralisation number NN<0.005 mgKOH/g, and on the **aged** oil with an acid NN of 0.18 mg KOH/g.

All of the paper inserts were initially dried in an electric kiln at 120C. The controlled residual water content in the paper was then well below 0.1%. A water content in the cellulose (Cp) of 1,2,3,4,5 and 6 % (by weight) and a system temperature range of 25C to 70C (by 5C increments) were selected for the experiment.

All paper inserts were saturated to the desired moisture levels by pumped hot oil immersion with sufficient time given to ensure exact equilibrium conditions were achieved before experiment measuring. The exact dosage of water was realised by weighting.

The experimental data for new oil are shown in Fig.2 , numerical values can be found in [L1].

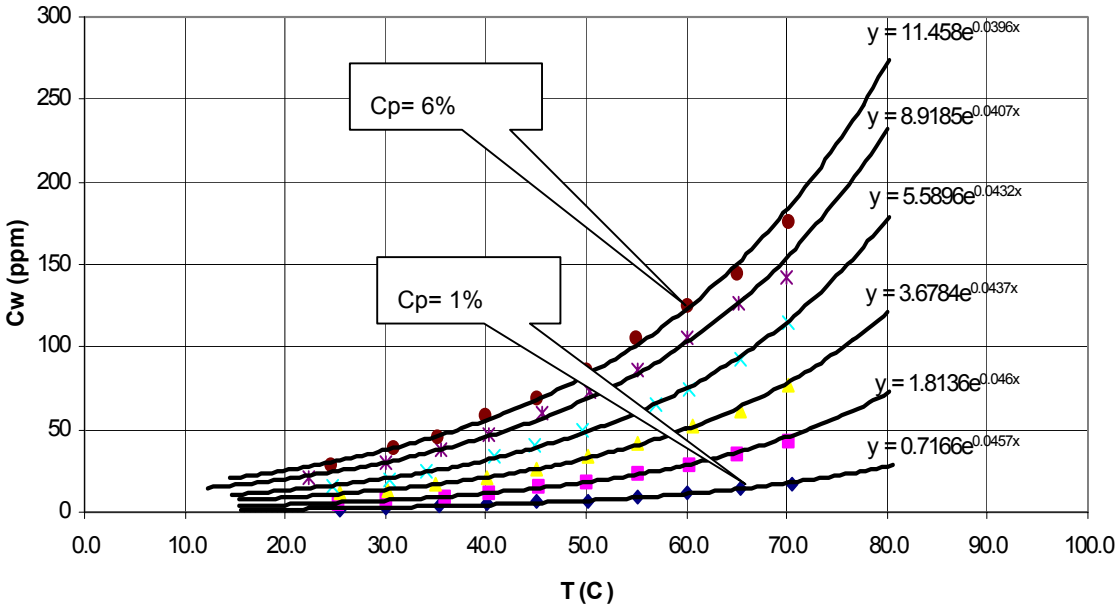

Fig. 2 Relation $C_{w,KF} = C_{w,KF}(Cp, T)$, NN < 0.005 mg KOH/g, KF method

First we have to determine the accuracy of the Karl Fischer (KF) method using the Aquameter, versus the water in oil HMP228 sensor, or method (F) in new oil. For this purpose Fig. 3 is used for verification. The HMP228 sensor measured values ($C_{w,F}$) are on the X - axis, and the Aquameter values are on the Y-axis ($C_{w,KF}$).

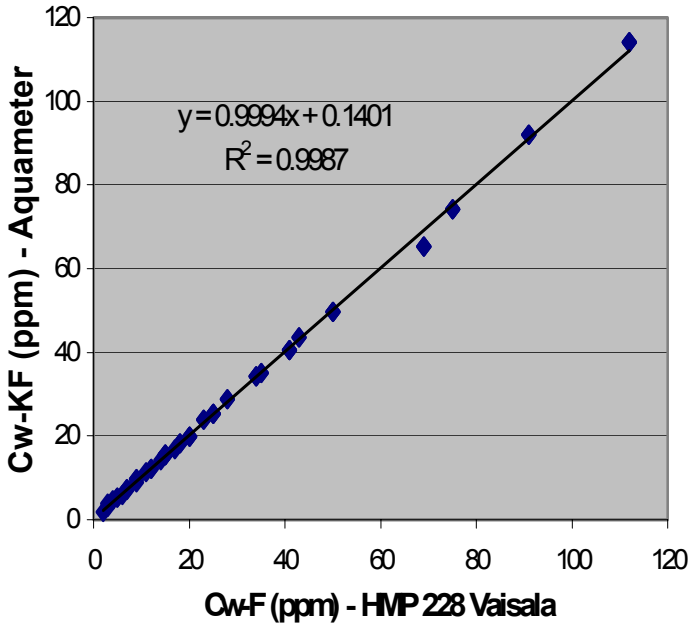

Fig. 3 New Oil - The correlation of KF versus Sensor F method.

The values measured by both methods are reasonably close. The correlation index R^2 is near 1 (R2 = 0.9987) and the accuracy of both methods is therefore considered equivalent.

However when aged oil (NN = 0.18 mg KOH/g) was used in the experiment, quite different results were evident. The results are shown in Fig. 4.

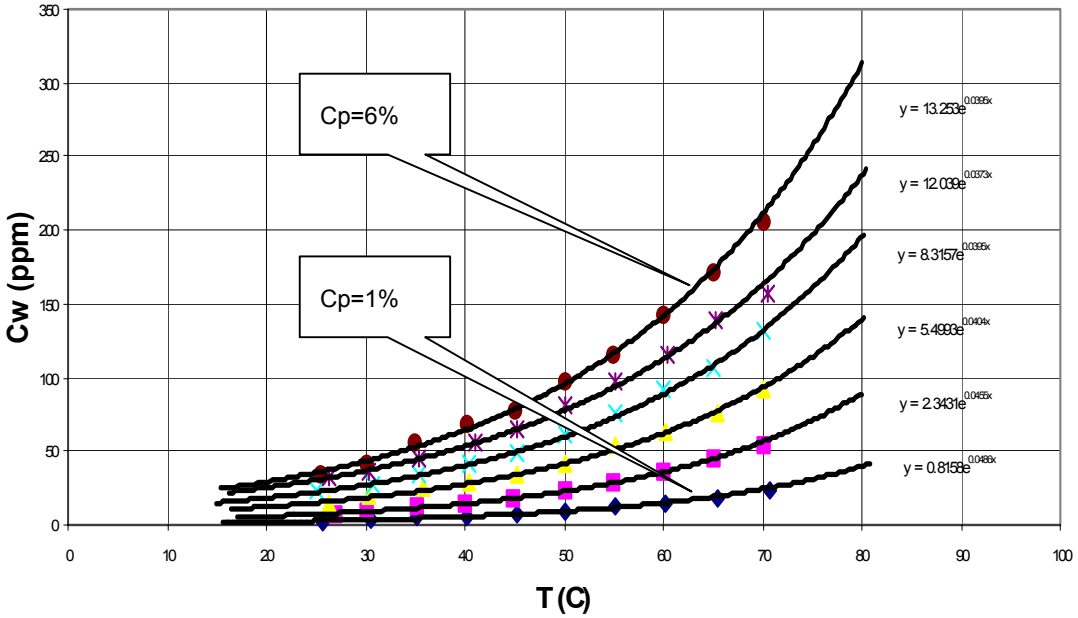

Fig. 4 Aged Oil (NN = 0.18 mg KOH/g) - Relation Cw = Cw (Cp, T) , KF Aquameter method.

The Aquameter now reads markedly higher Cw values at exactly the same Cp and T levels. The variance in measurements can be very easily identified in diagram in the Fig.5.

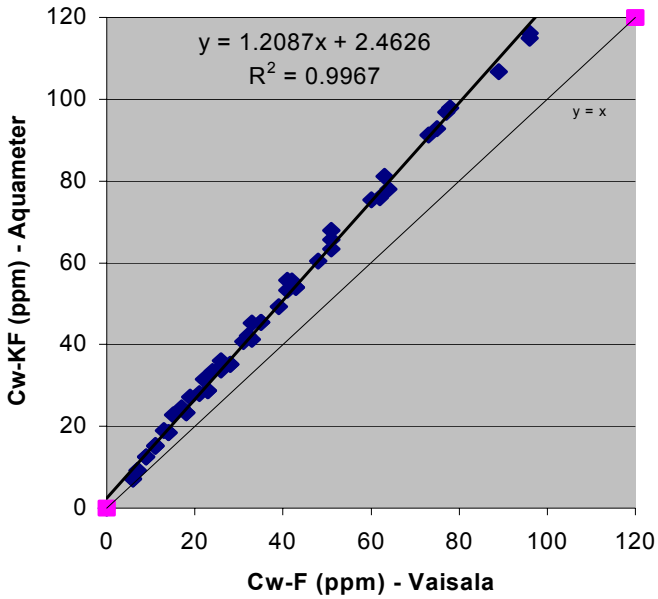

Fig. 5 Aged Oil (NN = 0.18 mg KOH/g) - Correlation between the KF and F method -

Now, the clear linear deviation is visible between the KF a F. The deviation gradient is more than 20%, and moreover the correlation index R^2 of the new linear trend is very high again. Because only the NN values have changed, this deviation is a direct result of the ageing products in the oil.

The sensor F method for has been used for comparison with the KF method, bringing the new and aged oil results together confirms that the F results are not adversely affected by NN variation.

The evidence is given by following verification diagram at Fig.6

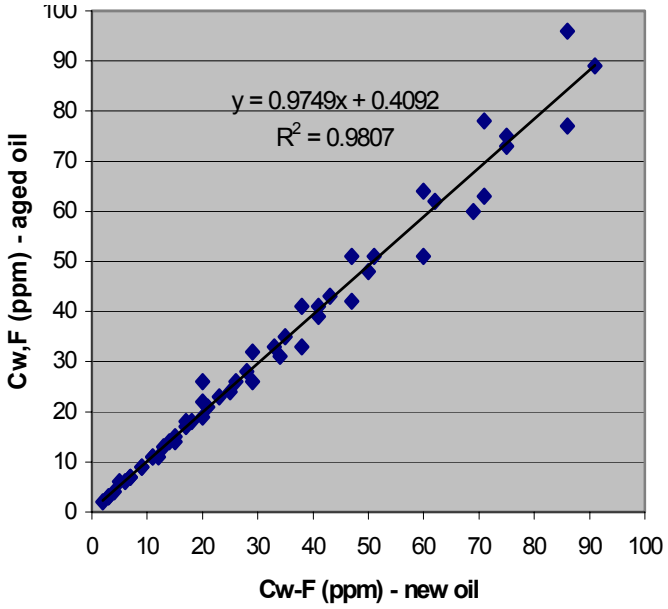

Fig. 6 Correlation of sensor F methods: new oil versus aged oil (NN = 0.18 mgKOH/g)

From the detailed experiments, It is very clear that the accuracy of the sensor F method is not affected by the aging by-products and NN value, and that the F method measures only the dissolved water that moves in and out of the oil-cellulose system with temperature.

The water in oil results of the KF methods are, on the contrary strongly dependent on the aging by products and NN value. This method can not be used for the accurate estimation of the moisture contamination of power transformers, as the Cw deviation increases with a NN value increase.

The second potential problem which is tightly connected to the moisture diagnosis of power transformers is the accuracy of many currently used Nielsen equilibrium diagrams.

4. Verification of Nielsen equilibrium diagrams

The experimental apparatus gave a good opportunity to compare our measured results with many well known equilibrium references [L2]. Fig. 7 shows our test results in the well known form of Nielsen relation Cp= Cp (Cw, T) .

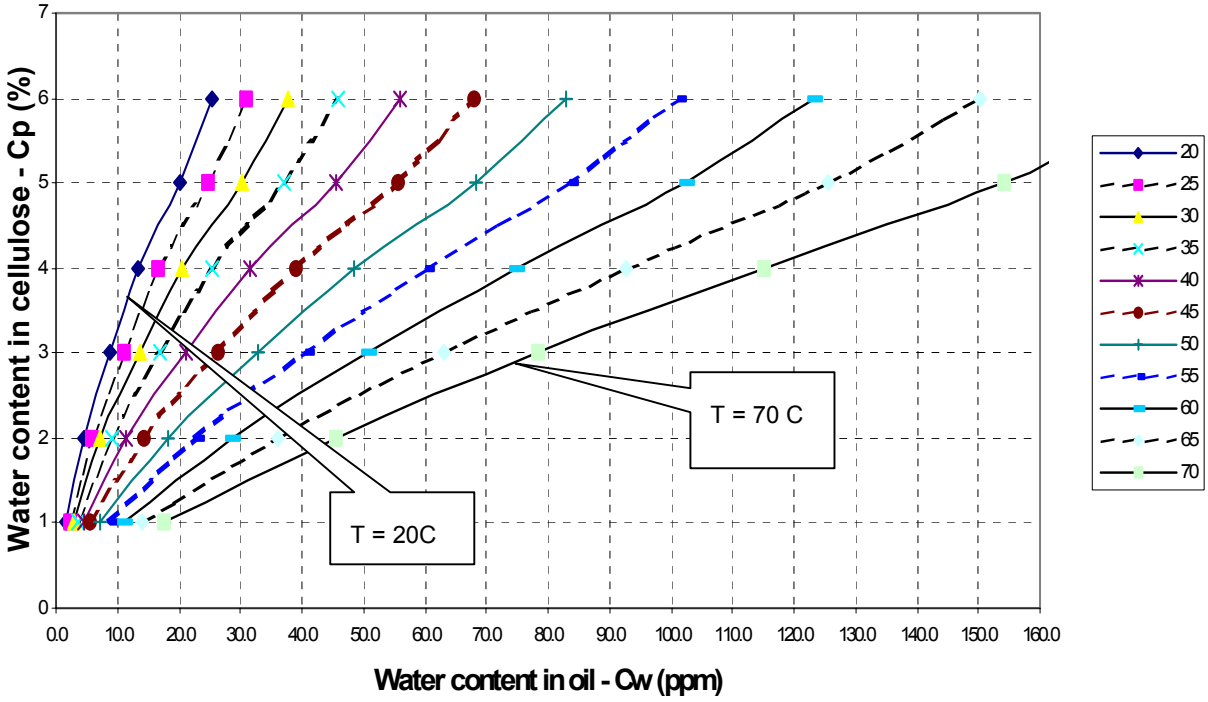

Fig.7 Nielsen diagram based on experiment data, (new oil NN = 0.005)

An unbiased comparison of Nielsen diagrams and our own experiment data is used in the comparative diagram Fig 8.

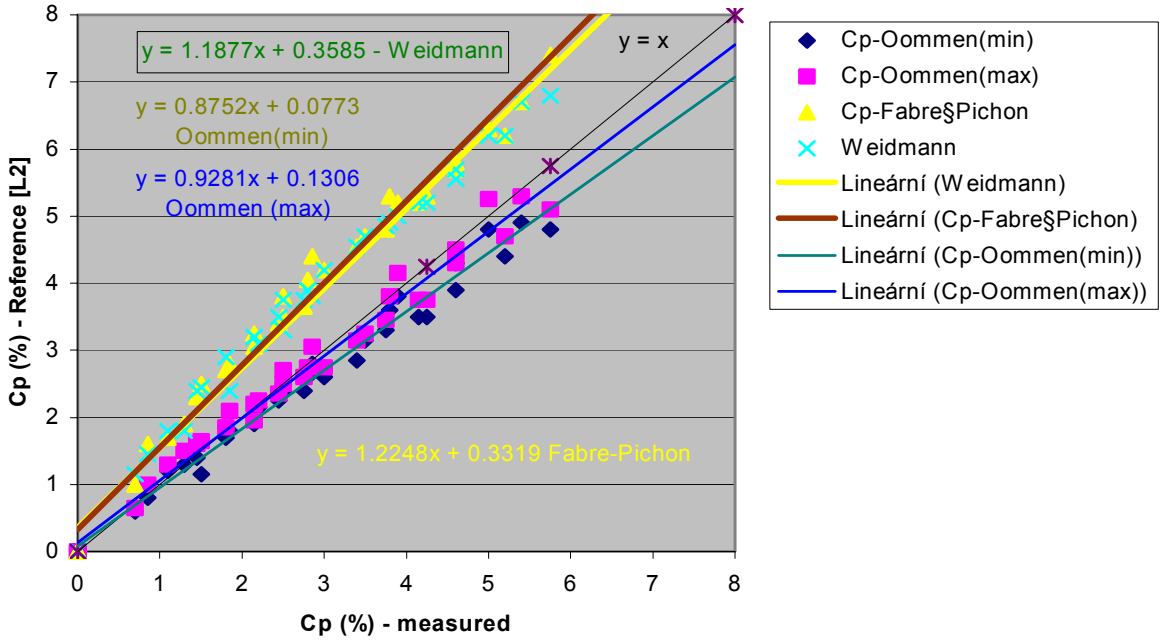

Fig. 8 The correlation between Nielsen reference data - experimental data

Only the new data from [L2] is consistent with our results. The most well known and used equilibrium diagrams (Fabre-Pichonem (1960) and Noriss (1963 - EHW-Weidmann), clearly over estimate the water in paper (Cp) values over the whole range of Cw and T. On the other hand, the Oommen data ([L2] -1983), is the closest to our own findings, with an acceptable 7% deviation from our values.

5. Conclusion

The diagnostic discrepancy between new and aged oils mentioned in the Introduction, is now easily explained.

The KF method measures not only diluted water in the oil, but also the water which is bound in the aging products of the oil. It means, the KF reading of the water content in the oil before and after the change of the oil inventory of the transformer is, and has to be, always different between the old (aged) and new oil.

If we use F method, where the sensor reads only the dissolved water, we get the same readings.

Consequently - the water content in the cellulose materials of the transformer remains basically the same before and after the oil change. The wide-spread opinion that a transformer can be dryed by the aged-new-oil change (or by the oil regeneration) is therefore in principle wrong.

To properly calculate the moisture in the oil–cellulose system, it is only important to measure the dissolved water because only this water migrates between the oil and cellulose.

The second shortcoming of present diagnosis is the fact that the older Nielsen diagrams overestimate the Cp values. This coupled to the KF over statement can result in a highly overestimating of the water content in the cellulose and consequently to the misleading diagnostic results.

If we use the F method and the proper Nielsen diagram, the deviation is very low between the new and aged oil, greatly improving the accuracy of diagnostic results.
Literature:

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