Setting Control Limits for Water Contamination In Hydraulic and Lube Systems

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Synopsis

This paper explains the harmful effects that the presence of water has on both the oil based lubricant and hydraulic fluid and its consequential effect of the life and reliability of oil wetted systems. It introduces a new method of measuring the water state of the oil directly in-line, so that the measurement is continuously available and corrective actions can be quickly implemented if there is an "out of limit" situation, so that damage to both the components and lubricant is minimized. The paper also shows how water specifications can be derived to provide basic protection to systems and also to enhance bearing life, based upon individual requirements.

1 Introduction

It has long been recognized that the presence of dirt in the hydraulic or lubricating oil can be responsible for about 50 to 60% of all failures in oil wetted systems [1, 2]. In the '80s & 90s these studies prompted a review of the design, build and operational procedures with the intention of reducing the incidence of dirt related failures. As a result, particulate contamination levels have fallen substantially [3], and system performance and reliability will have improved greatly as a result. The emphasis has moved from controlling contamination to maintaining cleanliness. More and more companies are taking a holistic approach and are applying "Total Cleanliness Control" over their fluid systems as they see that this route can realize both immediate and substantial improvements in efficiency and more profitable use made of fluid processes [4].

The work by Rabinowicz [1] showed that corrosion, caused mainly by the presence of water in the lubricant or hydraulic fluid, accounted for 20% of all failures to equipment. With the reduction in the levels of particulate contamination, systems have become progressively cleaner and more reliable as a result [5], water has now become proportionately more important as a source of unreliability. Thus, the control of water in the oil must be addressed if the life and reliability expectation of users are to be realized.

Measurement is the basis of control and instruments are now available that measure the water state directly in-line so that the result is continuously available. This immediately available reading means that corrective actions can be implemented if there is an "out of control" situation. As this can be done with the minimum of delay the damage to both the components and lubricant is minimized. The data has to be compared to a specification and this where substantial improvements have to be made, and is the subject of this paper. This paper explains the effects of water on both components and the lubricant, briefly details the methods of measuring the levels of water in oils and presents the latest in-line device. It then explains how to set control limits based upon individual requirements rather than 'third party' recommendations and presents the economic benefits of using dry oils.

2 Water in Oil

Water can be present in the oil in three states:-

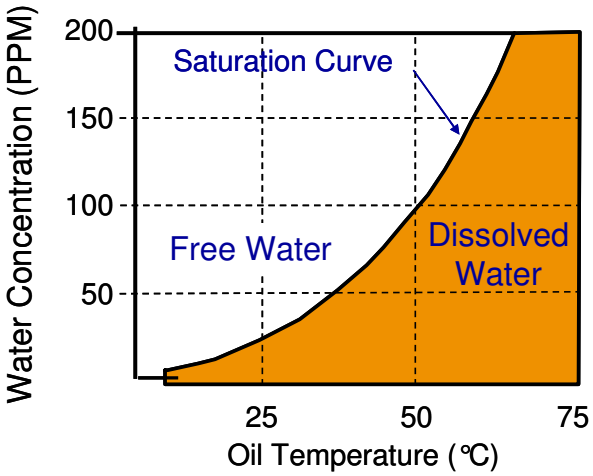
a) Dissolved

Small quantities of water will always be bound up in oil at the molecular level and the oil usually has a 'clear' appearance, provided that it is not too oxidized. The amount of water oil that can dissolve in the oil will depend upon the type of base stock used, its condition, its additive package and the temperature. The point at which oil cannot hold any more water is called the ***saturation point***, and it is temperature

dependent. For instance, a new, highly refined parafinic circulation oil with few additives will hold little water before becoming saturated (say 100 ppm at 20ºC). At the other extreme, oils sometimes used in ship-board hydraulic systems or those used rolling mill applications can have saturation levels of 4,000 ppm at 20ºC. This is because they have to keep relatively large amounts of water in suspension before allowing free water to coalesce and form large droplets. Synthetic oils, because of their chemistry have a 'natural' tendency to hold water and so have high saturation levels (say 4,000 to 8,000 ppm at 20ºC) depending on type.

The dependence on temperature is shown pictorially in Figure 1, which shows the effect of temperature on the saturation characteristics of oil with increasing temperature. If the oil has a fixed amount of water say 100 PPM at 60° C, all of the water will be dissolved. If the temperature reduces free water will occur at about 50° C.

Figure 1 Effect of Temperature on of Oil's Saturation Characteristics



b) Free Water

Free water occurs when the oil can no longer hold any more water it comes out of solution to form microscopic droplets and the oil becomes hazy at this stage. Any further increase in water content or decrease in temperature will cause more water to come out of solution. These droplets can coalesce together to form larger droplets. If the relative density (S.G.) of the oil is <1.0 and the oil is stationary, the water will fall under gravity, perhaps into 'dead' areas such as reservoirs, gear casing etc. In the case of some synthetic oils where the relative density (S.G.) of the oil is >1.0, these will gradually rise to the free surface provided that there is little disturbance.

c) Emulsified

When free water is present and the oil is subjected to shearing action as occurs in pumps, gears and control valves etc., the water is broken down into small relatively stable droplets and these can be held in suspension; oils used in applications where water abounds, are formulated to promote emulsification rather than separation. In this state the water will affect the properties of the oil and hence the wear rates will increase but the water will not have a significant affect on the system corrosion rates.

3 Effects of Water in Oils

The presence of water in the oil can have wide ranging effects, and these are summarized below:

- **Reduced lube film thickness**
- **Loss of lubricity**
- **Increased compressibility**
- **Fluid Oxidation**
- **Additive depletion**
- **Accelerated surface fatigue**
- **Corrosion of component surfaces**
- **Icing at low temperatures**
- **Bacterial growth**

Loss of fluid properties hence increased wear to components

Some of these are major and some are minor, but it is the authors' opinion that the greatest effect of water on the oil is to reduce the properties of the oil particularly its ability to lubricate and protect the component. This damaged the component surfaces through increased wear, and the effects are triple edged:

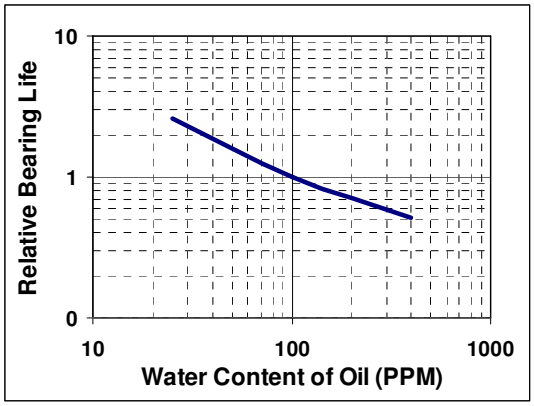
- The presence of water accelerates the decomposition rate of the oil through oxidization, especially when particles are present. The presence of reactive particles like iron and copper in combination with water greatly increases the degredation rate [6].
- Water in the oil reduces the lubrication film and exposes the moving surfaces to increased wear through abrasion, adhesion and fatigue.
- The presence of free water increase the compressibility of the oil in the contract zone of bearing surfaces which further increases the wear rates and leads to a regenerative wear situation.

A factor that is often overlooked is that the acidic products are polar and have a high affinity for water. They readily dissociate from the oil to the water phase making the water more acidic and thus accelerate system corrosion rates.

Another serious effect is on the fatigue life of rolling element bearings. This was studied by Cantley in 1977 [6] who investigated the effect that both free and dissolved water had on the fatigue life of bearings. Most of his work was done with an SAE 20 mineral oil at 65.5ºC (150° F), a stress level of 2.03 GPa, and a speed of 2700 RPM. Water concentrations of 25, 100 & 400 PPM were used and the life of 32 bearings was evaluated at each condition. The $L_{15.9}$ Weibull life estimated. This is presented in Figure 2. This data was used to obtain the much used relative bearing life factor L:

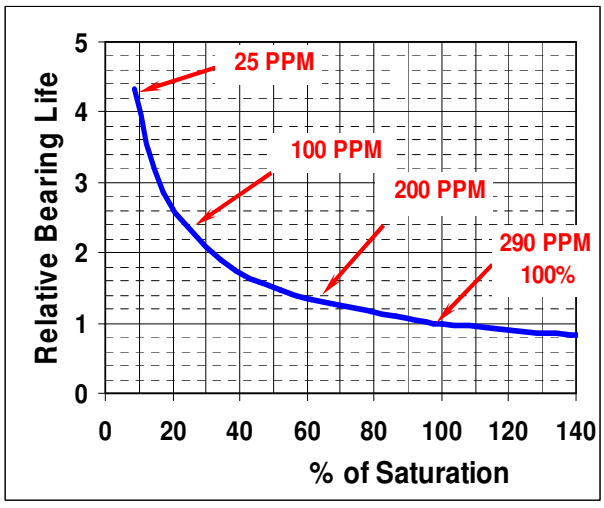
$L = (100/X)^{0.6}$ where L= Relative life to 100 PPM, X= water concentration in PPM.

Figure 2 Effect Of Water Content On Bearing Life –R E Cantley ,



A less well known part of Cantley's work was the investigation into the saturation characteristics of various oils. Unfortunately these tests were performed at 38 °C not at the bearing test temperature of 65.5 °C so there is no direct relationship to the % Relative Humidity (or % of Saturation). However knowing the oil type and the water content at a saturation temperature, the water content to give saturation at the bearing test temperature can be realistically estimated. This is calculated as 290PPM

Figure 3 Effect Of Water State On The Fatigue Life Of Rolling Element Bearings



The above equation can be used to study the relationship between the water state (% RH or % of Saturation) and the relative bearing life. Values of L have been calculated over a range of PPM values and the3 derived saturation value for the test oil is then used to calculate the %RH at the PPM values. The results are seen in Figure 3.This graph shows some surprising results. The data has been truncated at 140% RH or 400 PPM as there is no experimental data beyond this. However, it shows that if free water is present then only a small increase in bearing life can be expected when a significant reduction in water content is made. It is only when the water state becomes dissolved and dry (< 40%) can significant improvements in bearing life be achieved. This makes it essential to operate bearing systems with oil that is always below its saturation level and the drier the better. If the bearings function with dry oil (say 20% RH) then the life of the bearing can be increased by about 2.5 times the life achieved when at the 100%RH level.

This trend is somewhat surprising as it was the authors' understanding that the reduction in bearing life was caused by a combination of reduced lubricity and hydrogen embitterment in the fatigue cracks. It is therefore logical that greater increases in life should result when proportionate reductions in the levels of free water are made compared to similar reductions in dissolved level. As this discussion is beyond the scope of this paper, no further discussions are made.

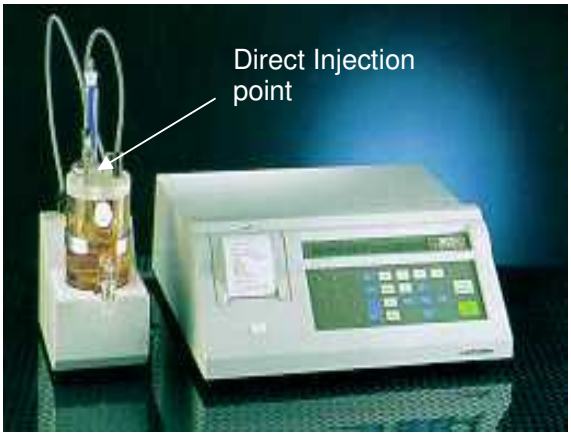
4 Measurement of Water Content

There is a wide variety of methods for determining the water content of oil and it is beyond the scope of this paper to discuss these as the choice of which method to use depends upon the purpose for monitoring, as much as the speed and accuracy required. Also, most are laboratory based so there is obviously a delay between taking the sample and receiving the results Two methods will be discussed, the Karl Fischer Titration [6] method as this has become the most widely used "off-line" method and the recently introduced capacitive water sensor that measures the water content directly in the system flow line.

a) Karl Fischer Titration Method

This is the most widely used method both in the laboratory and on- site, because if its ease of use, generally short analysis time (about 2 minutes for the direct injection method), ability to analyze a wide range of water content (typically 2 to 5,000 PPM) and good accuracy of repeatability (< 2% depending on water concentration). A view of the instrument is seen in Figure 4. It works on the Coulometric (electrochemical) Titration principle, where the water in the oil is converted proportionally into iodine and the amount of iodine is measured by the instrument. The oil sample is injected into the cell after its volume or weight has been measured. The instrument gives the PPM by weight or volume.

Figure 4 View of Coulometric Titration Equipment



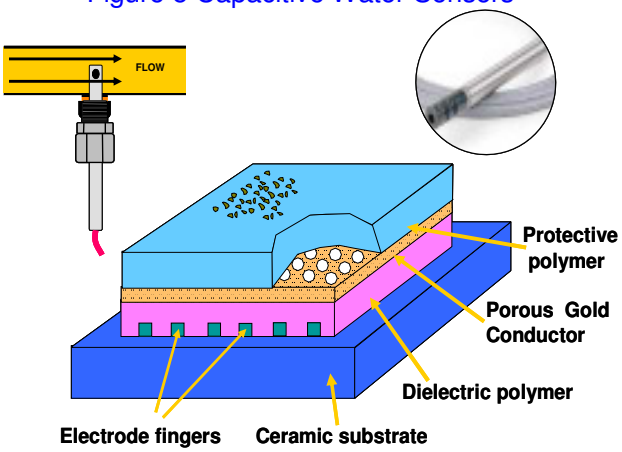
Despite its considerable advantages, the reading is affected by certain additives contained within the oil, principally those that are zinc based, but also those that bind the water molecules in the oil's structure. These usually increase the water content readings. This is overcome by either changing the reagent or by boiling off the water in an evaporator and injecting it into the cell using dried nitrogen. This increases the analysis time and also the variability in measurement, especially with dry oils.

a) Capacitive Water Sensor

This instrument is a development of the successful air moisture sensor. It consists of a capacitive cell formed by sandwiching a dielectric polymer between gold electrodes. The lower electrode is deposited upon a carrier substrate which is impervious to moisture whilst the upper capacitor plate allows the transmission of water molecules, but not other materials like additives. Water molecules migrate into or out of this layer depending on the humidity of the polymer relative to the oil This alters its dielectric constant and thus the capacitance of the capacitor. This change in capacitance is then converted into a signal proportionate to relative humidity of the oil. The instrument can display "% Sat" directly and PPM given calibration on the oil to be used.

The instrument is designed for in-line analysis where the probe is inserted directly in a major flow line. .

Figure 5 Capacitive Water Sensors



With this instrument data is immediately available both visually on a local display and in a control room via Ethernet, BUS or wireless data transmission protocols. Thus corrective actions can be taken long before an “out of limit” situation occurs and becomes a problem. Maintenance moves from a reactive regime to a proactive one, and this ensured that the plant operated at its optimum efficiency. Perhaps of greater importance for the operator is that wear rates will be minimized, corrosion should be eliminated and reliability enhanced.

5 How to Select Maximum Water Levels

It is the authors’ opinion that this aspect is perhaps reminiscent of the ‘dark ages’, as there does not appear to be an documented method to enable operators to select the level that is appropriate for their system and requirements. All too often, certainly in bearing systems, we hear “200 PPM” being stated as the optimum level without any technical basis for it. From section 3 we see that 200 PPM may be adequate for some but not give the life and reliability that others require. So, how should water levels be selected?

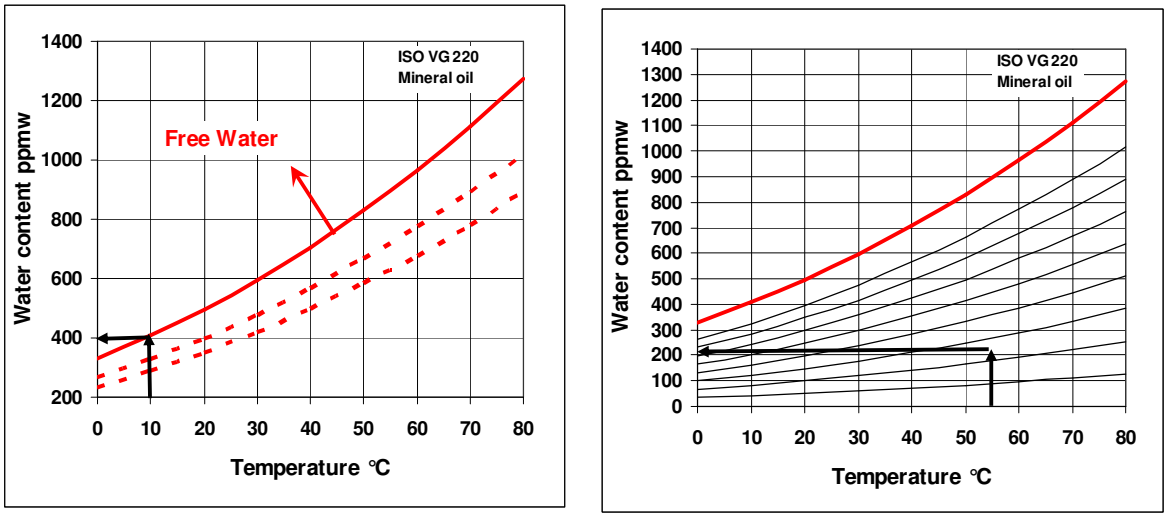
As we see it there are two ways of selecting these levels depending upon the level of control required. In this paper these are termed the "Protection Level" and the “Life Extension Level”.

a) Protection Level

Here the philosophy is to avoid the formulation of free water as this will eliminate both system corrosion and many of the factors identified in Section 2. For this the user needs to know two factors: firstly, the lowest temperature that the system will be exposed to (accounting for cold draughts!) and this is nearly always experienced when the system is stationary, and secondly, the saturation / temperature characteristics of the oil as seen in Figure 4a.

Figure 4 Saturation Characteristics For A Paper Machine Oil

a) Protection b) Life Extension



Using Figure 4b, the user selects the minimum temperature and interpolates the absolute water content (PPM) to give saturation point at this temperature, for instance if the minimum temperature of the system (and oil) is 10° C then the station point is 400 PPM. The user then decides on a factor of safety, (say 80% or even 70% of this valus), and this gives the control limit. For the 70 & 80 % levels the control limits become 280 & 320 PPM respectively.

If a water sensor is used then a output of PPM is the most convenient for comparing the output, but also displaying the % RH has the advantage that the approach of the saturation point (free water being formed) can be seen and more readily understood. It is worth pointing out at this stage is that the saturation point can both increase and decrease so reliance solely on PPM values cam be problematic.

b) Life Extension Level

This is an extension of the above process and is designed for bearing systems where a greater level of reliability and longer life is required. Here the data derived from the work by Cantley in Figure 3 is used to obtain the %RH value to give a certain life extension. For instance, if a life extension of 2 times is required the %RH value from Figure 3 is 25%. The user then uses an extended saturation curve like the one in Figure 4b to obtain the PPM value to give this %RH value at the operating temperature. For this example the control limit is about 210 PPM.

Although this paper has concentrated on the life of rolling element bearings, the life of journal bearings can be significantly reduced by running with a wet lubricant. Research has shown that the wear rate of a journal bearing running on oil with 1% water can be nearly 10 times that with dry lubricant [8}. However, journal bearings differ from rolling element bearings in that sulphurous products from oil and perhaps the process tend to dissociate to the water phase and have a greater effect on white and Babbitt metal bearings compared to the rolling element type

6 Conclusions

The demands on operators of fluid systems to improve efficiency by reducing failures and extending life have focused attention on reducing contamination levels. As particulate contamination is now under control (or should be!!) attention is being directed to water contamination. Water can have equally serious consequences on the life and reliability as it affects the properties of the lubricant, which in turn affects the wear rates of the system. Hence, like dirt levels, the control limits for water must be made of a system to system basis.

To successfully control water levels two factors are required, a speciation or the maximum permissible water content for the oil being used and a means rapidly monitoring the moisture content so that prompt corrective actions can be implemented to limit the damage done should an “over limit” situation occur.

There does not appear to be a rational method for selecting oil moisture levels based upon individual system and user requirements and the methods proposed in this paper were developed for that purpose.

The introduction of the capacitive water sensor is a significant advance in the maintenance and management of systems as data on the moisture is now immediately available. Thus corrective actions can be taken long before an “out of limits” situation occurs and the increase in wear rate that will accompany an increase in moisture level will be minimized, corrosion should be eliminated and reliability enhanced. Maintenance can then move from a reactive mode to a proactive one, and this will ensure that the plant is operated at its optimum efficiency and best use is made of maintenance staff.

7 References

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