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ABSTRACT

It has been recognised for many years that the majority of failures in fluid power transmission components can be directly attributed to contamination. Furthermore, it has been observed that the size and concentration of these contaminant particles effects the wear rate of components. As a consequence of the reduction in acceptable dimensional tolerances of electro/hydraulic actuators, the acceptable cleanliness levels of fluid power oils have also reduced.

Full-flow barrier media filtration alone can no longer cope with the necessary cleanliness levels for the smooth and consistent operation of electro/hydraulic actuators over their desired service life. By-pass filtration is the key to controlling oil cleanliness between services. Unfortunately, traditional barrier media filters of a suitably low micron rating tend to be excessively large to meet the desired service interval. However, centrifugal by-pass filtration offers a solution to controlling the oil cleanliness level without compromising filter size.

This paper briefly explains the principles of traditional barrier media and centrifugal by-pass filtration and highlights some of the advantages that self-powered centrifugal oil cleaners have over barrier media filters such as the physical size difference over similar service life. By-pass centrifugal oil cleaners are shown to offer excellent cleanliness control when operated under optimal conditions. It is these optimal conditions which are addressed in detail by this paper. The paper concludes by presenting some laboratory test results showing how contamination control can be achieved using a self-powered centrifugal oil cleaner in by-pass. It is demonstrated through laboratory testing, that through careful rotor design and control of operating conditions, significant improvements to fluid cleanliness levels can be maintained.

INTRODUCTION TO OIL CLEANLINESS CONTROL

Lubrication and fluid power system designers are well aware of the role that oil cleanliness can play in maintaining the life of moving components. A number of papers have been presented on the subject of contamination control and hydraulic circuit component wear in recent years [1]-[5]. Unfortunately, traditional full-flow filtration can no longer cope with the fluid cleanliness control necessary for acceptable service life of actuators and components. This has led system designers to employ additional techniques such as by-pass filtration to remedy the problem.

The technique of by-pass filtration is by no means new and automotive lubrication engineers, particularly diesel engine lubrication engineers are now beginning to reap the benefits that this technique offers, such as better viscosity control and extended service intervals [6][7][8]. The automotive industry currently uses two common by-pass filtration techniques, barrier filtration employing high performance low pore size filter media which needs a large surface area in order to sustain service life, and self-driven centrifugal oil cleaners which use the centrifugal sedimentation principle of separation to clean the lubricating oil to an acceptable level over the duration of the service interval.

Federal-Mogul have found in recent years that the role a full-flow filter plays when used in conjunction with a by-pass filtration technique is not well understood by many system designers. A full-flow filter in conjunction with a by-pass filter should be considered as the insurance policy for the system and sized so that it will remove particles from the system that may cause catastrophic failure of a critical component. The by-pass filtration technique then becomes the fluid cleaning device removing contaminants from the system and retaining them safely during the service interval.

The principles of full-flow and by-pass barrier media filtration are well documented and understood by many engineers. However, this is not true for self-driven centrifugal oil cleaners, particularly when applied to fluid power systems. Several papers have been presented on the subject of centrifugal separation in the recent past [6][7], however, these have either been specific to motor driven separators or for the capture of carbon "soot" deposits from diesel lubricating oils. Although the underlying principles are the same, the cleaning of fluid power oil systems present different challenges than those of diesel lube oils. This paper address the issues and concerns associated with the use of a self-powered centrifugal oil cleaner within a fluid power system such as contaminant separation and contaminant retention.

This paper briefly describes full-flow barrier media filtration and goes on to discuss the role by-pass filtration has to play in the total oil cleanliness process. This is followed by a short section on the operating principles of a self-powered centrifugal oil cleaner and the theory of centrifugal sedimentation. A closer look is taken at the installation and novel contaminant retention devices to minimise "wash out" from the rotor such as a retention cone and hot start technique. The paper concludes with a discussion on the type of artificial contaminant that should be used in laboratory test studies and a typical laboratory experiment showing how centrifuge rotor wash out can be minimised.

FULL-FLOW BARRIER MEDIA FILTRATION – Figure 1 shows a typical circuit diagram of the power pack of fluid power system. Fluid power circuits tend to consist of a mechanically driven oil pump, an oil pressure relief valve, pressure sensors, oil cooler, hydraulic cylinders, actuators and a combination of oil filters. Typically there will be at least one full-flow filter and possibly a by-pass filter. The full-flow filter or filters are used to prevent contaminant particles greater than a given size reaching the critically toleranced components causing accelerated wear and ultimately failure. The characteristics of a full-flow filter are its ability to remove particles greater than a given size (absolute rating) whilst allowing high flow rates with an acceptable pressure drop across the filter element. The pore size rating of a typical full-flow filter in a fluid power application can range anywhere between 30 - 100µm (differences often stem from the confusion over the use of absolute vs. nominal filter ratings). Generally to achieve an acceptable pressure drop across the filter element the element needs to have a large surface area. To enable this and to be packaged in as small a space as possible, the barrier media element is pleated as shown in figure 2. Unfortunately, even employing the best pleating methods the size of a full-flow filter that gives an acceptable service life is still cumbersome and restrictive. Hence, full-flow filter manufacturers are constantly juggling and making trade off's between element pore size, filter life, flow rate, pressure drop and physical filter size.

It has been shown that the level of component wear within a hydraulic system is a function of the level and size of contaminant in the hydraulic oil [4][5][9]. In general lower particle concentrations and smaller average particle sizes give longer component life.

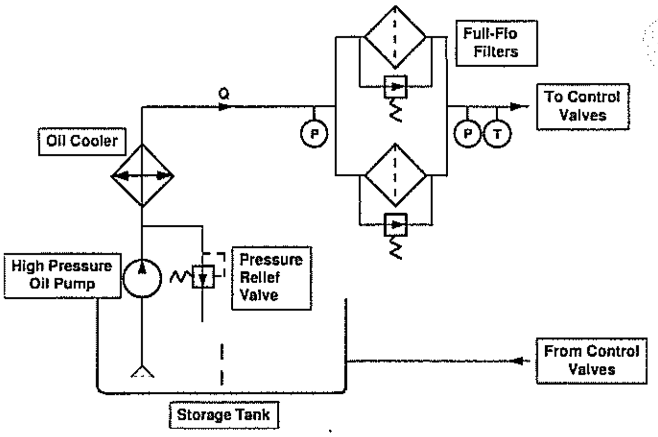

Figure 1. Typical Circuit Diagram Of A Fluid Power System

It is clear that the level of fine contaminant particles needs to be controlled, however conventional full-flow barrier media filters are at best an order of magnitude larger in pore size than the majority of particles circulating in the hydraulic oil [5]. Full-flow filters therefore have little capability to remove these fine particles from the hydraulic circuit. By-pass filtration offers a solution to the problem of cleaning the oil to a high level of cleanliness.

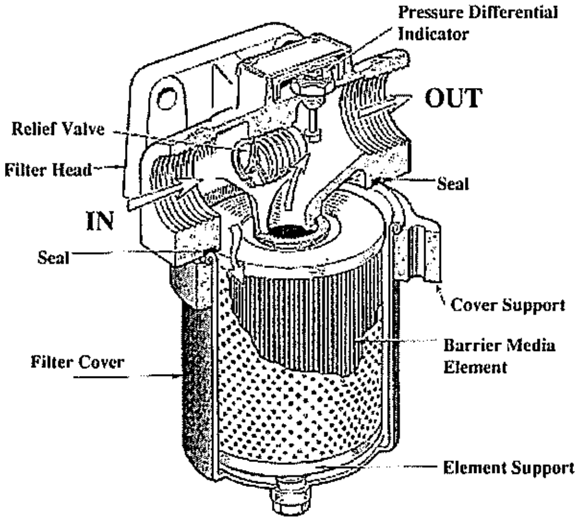

Figure 2. Construction Of A Typical Barrier Media Filter

BY-PASS OIL CLEANING – By-pass cleaning, as it's name suggests cleans or "filters" the oil to a high level of cleanliness in a by-pass loop. The principle of by-pass filtration is to remove some of the oil from the system, pass it through a filter where a significant proportion of the contaminant is removed. The now cleaner oil then returns to the settling tank (figure 3). This is a continuous process whenever the hydraulic power pack is in operation. Through this method high levels of cleanliness can be achieved provided the correctly sized by-pass filter is selected. The level of cleanliness that can be achieved is dependent upon a number of factors such as by-pass filter flow rate, sump size, ingression rate, by-pass filter instantaneous efficiency and capacity.

There are two basic types of by-pass oil cleaning device on the market, barrier media devices and centrifugal devices.

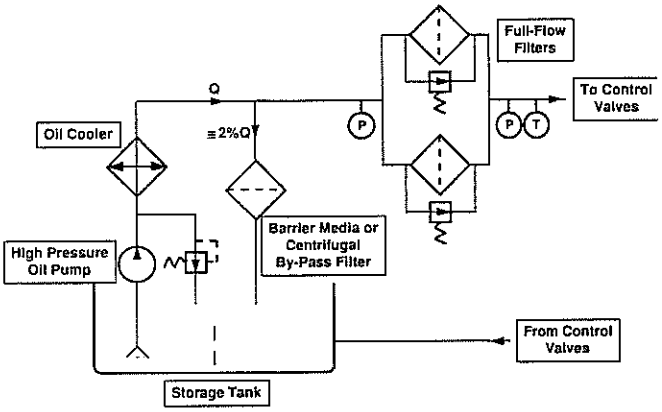

Figure 3. Typical Circuit Diagram Of A Fluid Power System Containing A By-Pass Filter

Barrier Media Cleaners – The principle of operation behind a by-pass barrier media cleaner is the same as a full-flow device, particles being removed which are greater than the pore size of the filter media, which would typically be in the order of 3-5µm absolute.

By-pass lubricating oil filtration in diesel engine applications is becoming increasingly popular with the worlds leading engine manufacturers as a way of controlling the level of contaminant by removing and storing it. In Japan, diesel engine manufacturers have been using increasingly complex combination barrier media full-flow and by-pass filters for many years. However in Europe, Scania, Renault and DAF are using self-driven by-pass centrifugal oil cleaners as are Mack in the US and a raft of other engine manufacturers around the world.

The benefits of using continuous by-pass filtration in conjunction with a traditional full-flow filter are two-fold. Firstly, cleaning the oil through a by-pass filtration process removes many of the very small contaminant particles that would go straight through a full-flow filter. They are also capable of removing some of the relatively large particles that would have normally been stopped by the full-flow filter and hence the use of by-pass filtration can extend the life of the full-flow filter. This gives the lubrication system designer the opportunity to either use a physically smaller full-flow filter or possibly to extend the oil service life [8]. Secondly, an appropriately sized by-pass filter can remove the small pro-wear contaminant particles thus extending service and component life, thus reducing operator costs [3].

Centrifugal Oil Cleaners – An alternative form of by-pass filtration device is the centrifugal oil cleaner. These fall into two broad categories of powered and self-powered. The powered types are generally large and expensive units, however, these have found extensive applications in process industries and on very large marine diesel engines cleaning both the fuel and lubricating oils. Self-powered centrifugal oil cleaners are generally much smaller than their powered counterparts and have found applications in many fluid cleaning processes such as diesel lube oil cleaning, industrial quench oils and hydraulic oil cleaning.

Figure 4. An Open Centrifuge Rotor From The Lubricating System Of A Diesel Engine Reveals ATypical Deposit Of Removed Contaminant

A self-powered centrifugal oil cleaner uses the oil supplied to it to be cleaned, which is supplied under pressure, to drive the cleaning rotor, hence the term self-powered. Once cleaned, the oil returns to the sump or settling tank. A centrifugal oil cleaner uses the principle of centrifugal sedimentation to separate particles of different density and is therefore ideally suited to the cleaning of wear metals and ingressed silica particles from hydraulic oil. In a self-driven by-pass centrifugal oil cleaner these contaminants collect on the inside of the rotor, in a diesel lube oil application the contaminant binds to form a hard cake (figure 4), however, in a hydraulic oil application the soot binding agent is not present and the contaminant needs to be retained by some other means (see section "Centrifugal Filtration Of Power Transmission Fluids" following).

A centrifugal oil cleaner has two major advantages over a barrier media filter. Firstly the cleaning efficiency of a centrifuge remains constant throughout the service interval (providing the centrifuge has been correctly selected to match the ingression rate of contaminant and sump size). Secondly, the lower limit of particle size which can be removed by a centrifugal oil cleaner is the point where the viscous drag forces between the fluid and the particle equal the centrifugal force to which the particle is subjected. In practice this lower limit is well below 1µm in a hydraulic fluid power application.

PRINCIPLES AND THEORY OF CENTRIFUGAL OIL CLEANING

OPERATING PRINCIPLES OF A SELF-POWERED CENTRIFUGAL OIL CLEANER – The operating principles of self-powered centrifugal oil cleaners are simple but poorly understood and so it is worth spending a few moments to explain the basics. A far more detailed explanation is given in [7]. With reference to figure 5, a small proportion of the total system oil flow (≈2-5%) enters the vertical hollow spindle on which the rotor is supported. Oil exits the spindle via a cross drilling into an annulus between the bearing tube and the spindle. The bearing tube is used to keep the bearings at each end of the rotor in alignment and hence maintain good rotor speed at high oil supply pressures where stressing of the rotor may cause the rotor to distort. Oil exits the bearing tube via two optimised holes and enters the rotor's cleaning chamber 'A'. The contaminated oil is then accelerated up to the speed of the rotor and circulates around the outer wall (high g area) of the cleaning chamber as a consequence of the ribs in the top of the cleaning chamber[7]. Contaminants which are more dense than the fluid are deposited on the inner surface of the rotor wall via centrifugal sedimentation.

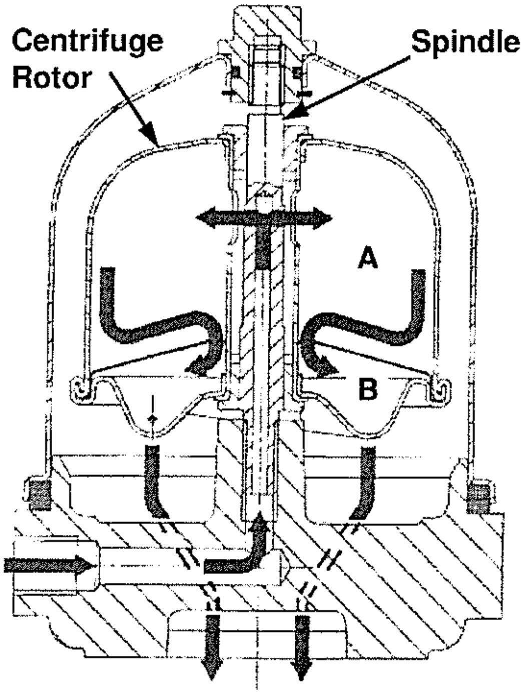

Figure 5. Centrifugal Oil Cleaner Principles Of Operation

The cleaned oil then flows from the cleaning chamber of the rotor into the lower drive chamber 'B' via an annular opening in the shallow cone which separates these two chambers. Once in the drive chamber the oil exits via a pair of tangentially opposed nozzles in the base of the rotor producing a reaction force which exerts on the rotor nozzles and hence causing the rotor to spin. It should be noted that the drive chamber 'B' of a centrifugal rotor is smoothly contoured to reduce fluid losses as the oil is transferred to the nozzles.

CENTRIFUGAL SEDIMENTATION THEORY – Centrifugal sedimentation is the key to how and why a centrifugal oil cleaner works. The basic principle can be explained thus: Consider a spherical contaminant particle of diameter d_p and density ρ_p suspended at radius r in a fluid with density ρ_o and dynamic viscosity μ_o and that the wh system is rotating at a constant angular velocity ω about a vertical axis, as shown in figure 6. Then it can be shown from Stokes' law that the time τ needed for a particle to travel a distance Δr from a start point at r to the rotor wall is given by

$$\tau = \frac{18\mu_o \ln((r+\Delta r)/r)}{d_p^2 \Delta\rho\omega^2} \tag{1}$$

where $\Delta\rho$ is the difference in density between the contaminant particle and the oil (ρ_p - ρ_o).

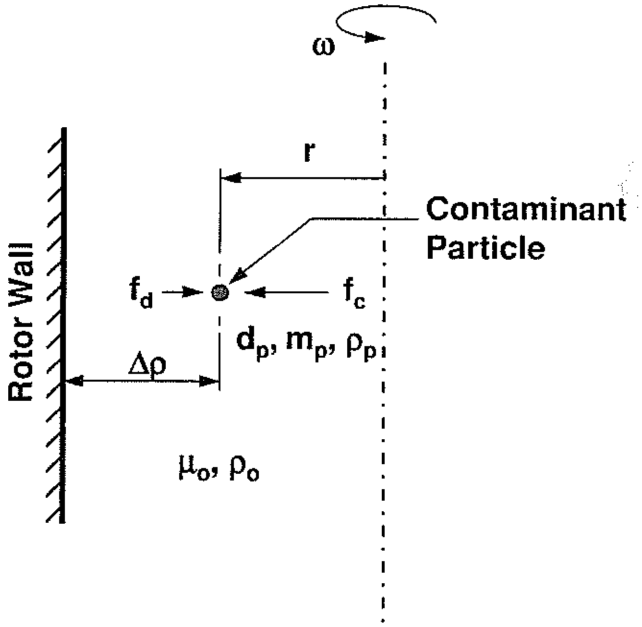

Figure 6. Centrifugal Sedimentation

From equation (1) it can be seen that the lower the viscosity the easier it is for a particle to travel through the oil and hence be removed from it. Hydraulic oils tend to low viscosity which is therefore good for particle separation. Secondly, for a given set of conditions, the shorter the distance Δr a particle has to travel to come into contact with a wall, the smaller the size of particles that can be removed. It should also be noted that the dominant terms in equation (1) are the two squared terms d_p and ω. Particle diameter (d_p) is a function of the contaminant however, rotational speed (ω) can be influenced by the centrifuge design. The importance of maximising ω is thus clear.

If we were to plot the single pass filtering efficiency η of a centrifugal oil cleaner for a particle/fluid system with a given density difference, $\Delta\rho$ against particle size where η is defined as upstream - downstream particle counts greater than a given size divided by the upstream particle count. The resulting curve will have the form given by figure 7.

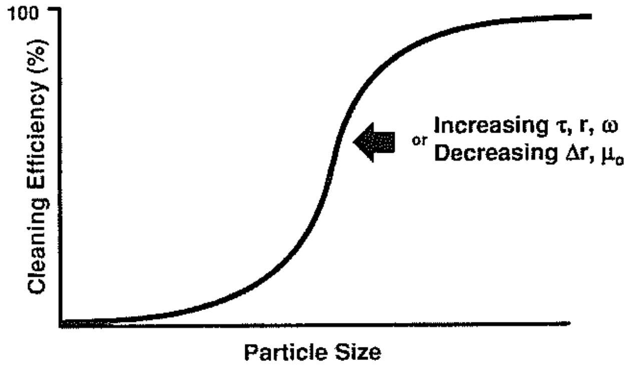

Figure 7. Oil Conditioning Considerations That Effect Centrifuge Cleaning Efficiency

To summarise, from figure 7 it can be seen that the horizontal position of this curve is a function of the terms in equation (1). Increasing the residence time τ, the radius of rotation r and the speed of rotation ω moves the curve to the left and hence smaller particles are removed. Similarly decreasing the distance a contaminant particle needs to travel Δr and the viscosity of the oil μ_o also moves the curve toward the Y - axis. Since the speed of rotation ω is the one dominant factor over which we have control, maximising the speed of rotation can be seen to be desirable since this increase the single pass efficiency of the rotor and decreases the minimum size of contaminant particles removed.

CENTRIFUGAL FILTRATION OF POWER TRANSMISSION FLUIDS

To optimise the cleaning performance of a self-powered centrifugal oil cleaner on any installation such as a diesel engine or fluid power system, consideration must be given to both the installation requirements and centrifuge rotor design. Installation considerations fall into two categories, oil supply and oil drainage. Centrifuge rotor design must also be considered since it can influence the cleaning efficiency of the filter and vary the retention of contaminant particles in the centrifuge rotor.

INSTALLATION CONSIDERATIONS There are two main installation considerations to be observed when designing a self-powered by-pass oil cleaning centrifuge into a fluid power system. These relate to the condition of the oil supplied to the centrifuge and draining of the cleaned oil away from the centrifuge and back into the settling tank.

Oil Supply – For the most efficient operation of a self-powered centrifugal oil cleaner it is important, for reasons of centrifugal sedimentation discussed previously, that oil reaches the centrifuge in the optimum condition. This effectively means that the oil should be hot, so that its viscosity is at its lowest, and supplied at a pressure which will be sufficient to allow the rotor to spin at high speed however, not so high that the rotor is stressed to such an extent that damage occurs.

To facilitate the requirements outlined above it is advisable to take oil down stream of the pump and upstream of the cooler. Oil from this point in the circuit will be hot and at highest pressure. In a fluid power system the pressure at this point is normally far too high for safe operation of the centrifuge and hence a suitable regulator is required to maintain a constant oil supply pressure to the centrifuge of typically 6 - 7 Bar (85 - 100psi).

In addition to tapping position, consideration should be given to ensuring that the oil supply galleries to the centrifuge are as short as possible and of adequate size to minimise pressure energy losses after the regulator.

Oil Drainage – Fluid drainage is vital to the efficient operation of a self-powered centrifugal oil cleaner. Fluid exiting the drive nozzles of the rotor gives up most of its pressure energy to make the rotor spin and hence has only potential energy due to its height above the settling tank to aid its return. Therefore, oil exiting the rotor must be allowed to escape freely from the centrifuge housing under gravity to return to the oil settling tank. Insufficient drainage causes flooding of the rotor and hence a significant reduction in both speed and performance.

Aeration of fluid power oils is another important point to consider. Through careful design of the centrifuge drainage port using baffles etc. and ensuring the fluid is prevented from returning to the settling tank close to the pump suction, aeration can easily be reduced to an acceptable level.

CENTRIFUGE ROTOR DESIGN – Centrifuge rotor design can influence two features of contaminant control. Namely, the collection rate of contaminant and the retention of collected contaminant. One feature which can extensively effect the rate of contaminant collection is the ribs in the top of the centrifuge rotor. A second feature which warrants explanation is the silt retention cone used to minimise the static wash out from the rotor when the rotor is stationary.

Ribs – Computational Fluid Dynamic (CFD) analysis of a centrifuge rotor has shown that the velocity vectors and hence flow path of the oil through the cleaning chamber of the rotor is far more complex than first imagined [7]. Federal-Mogul Oil Conditioning Systems have used CFD for a number of years to optimise the fluid flow path and hence optimise fluid cleaning performance without compromising contaminant storage space inside the rotor. One important feature being exploited to achieve this are the ribs in the cover of the rotor.

Due to the centrifugal force generated in the centrifuge rotor caused by its spinning action, a considerable pressure gradient is formed within the rotor which increases radially outwards towards the wall of the rotor as shown in figure 8. This phenomena is caused by the increase in centrifugal force as a function of the radius r. A proportion of the total energy supplied to the rotor is thus used in forcing the fluid entering the rotor towards the outer wall against this pressure gradient.

Through careful design of the rotor ribs oil is encouraged to flow to the outer wall of the rotors cleaning chamber (A in figure 5) subjecting the contaminant particles to high levels of centrifugal force. Hence, maximising particle separation and fluid residence time τ whilst maintaining an almost unrestricted flow of oil around the centrifuge cleaning chamber resulting in little pressure energy loss. This maximises the energy available at the tangentially opposed drive nozzles. Momentum transfer from the fluid exiting these nozzles is therefore maximised enabling high rotor speeds to be achieved.

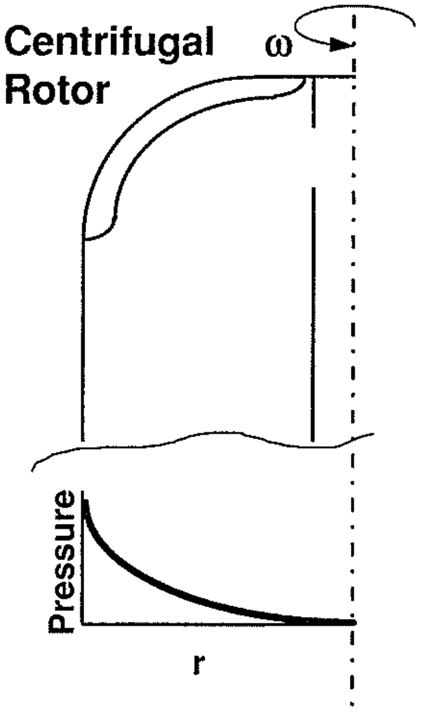

Figure 8. Pressure Gradient In A Spinning Centrifuge Rotor

MINIMISATION OF CONTAMINANT WASH OUT

In any filtration system, whether barrier media or centrifugal, the key to controlling the cleanliness of the fluid is the ability of the filtration system to remove the contaminant particles from the oil and store them for the duration of the service interval. Storing the contaminant during periods of shut down and restart present particular problems for any filtration device.

It has been observed in the field of barrier media filters that during the start up phase of a hydraulic fluid system when the oil is normally cooler and hence more viscous, higher than normal pressure differences can be generated across the barrier media filter which open the filter pressure relief valve, by-passing the filter element. The resulting action of this can cause the contaminant to be washed off of the filter element back into the system hence causing an increase in contaminant concentration level.

In a centrifuge, once the contaminant is captured in the rotor via centrifugal sedimentation, the challenge is to prevent it from escaping back into the system. Two for of wash out have been identified in centrifugal systems, static and dynamic wash out.

STATIC WASH OUT – In a centrifugal oil cleaning device, so long as the centrifuge is spinning at high speed then the contaminant is held compact against the side wall of the rotor. However, when the power pack is turned off and hence the rotor stops spinning the contaminant slumps to the bottom of the rotor. To stop the collected contaminant flowing back into the system under these static conditions an internal silt retention cone is fitted as shown in figure 9. This retains the contaminant until the rotor starts to spin once more and hence centrifugal force becomes dominant over gravitational force.

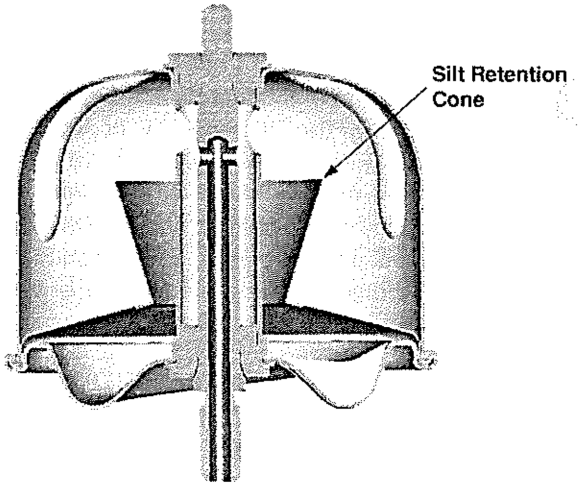

Figure 9. Silt Retention Cone

DYNAMIC WASH OUT – Dynamic wash out as its name suggests occurs when the centrifuge rotor is spinning up to speed when starting from rest i.e. when the power pack is restarted after shut down. As the centrifuge rotor starts from cold, contaminant is washed out of the rc (re-entrained) faster than it is being removed from the oil by centrifugal sedimentation. This occurs up to a point where the rotor speed and viscosity of the oil is such that the rotor is collecting more than is being washed out and from this point the level of contaminant in the oil starts to fall once more.

This phenomena can be minimised by not supplying oil to the rotor until it is sufficiently hot, thus reducing its viscosity. This will enable the centrifuge rotor to accelerate to a high speed quickly thus reducing dynamic wash out to an acceptable level.

CONTAMINANT WASH OUT LABORATORY TEST AND RESULTS

Two experiments were performed to establish the capability of the silt retention cone to reduce static wash out and to study the effects of only operating the centrifuge elevated temperatures, thus minimising dynamic wash out.

TEST CONTAMINANT – The aim of laboratory filtration testing is to evaluate the cleaning and structural performance characteristics of a filter in a controlled environment. It is often desirable that the conditions under which the performance characteristics are evaluated during the test mimic those observed in service. Centrifugal sedimentation relies on differences in the contaminant and oil density to remove particles, whereas barrier media filters remove contaminant particles based on particle size. To meet these testing requirements it is very important (particularly for centrifugal sedimentation devices) to select an artificial contaminant that is representative of the actual contaminant to which the filter is likely to be subjected in service. For this reason Federal-Mogul Oil Conditioning Systems have developed centrifuge testing specifications centered around two basic test contaminants [7].

If the filter is to be used in a transmission/hydraulic fluid power circuit where the contaminant ingress consists mainly of hard particles such as metallic debris and silica then the appropriate test contaminant would be ISO 12103-1 Medium Grade Test Dust (SAE 5-80) [10] as specified for the multi-pass filter test J1858 [11]. Depending on the application this may be cut with Iron (Fe) particles to represent metallic wear materials. Alternatively, for application to internal combustion engine lube systems (particularly for diesel engines) the most suitable standard test contaminant has been found to be SoftC-2A [12].

In the experiments described herein, ISO 12103-1 Medium Grade Test Dust has been used cut with Iron (Fe). ISO 12103-1 Medium Grade Test Dust consists mainly of SiO_2 (68 - 76% by weight) and Al_2O_3 (10 - 15% by weight), the remainder comprising small amounts of Fe_2O_3, Na_2O, CaO, K_2O, MgO, and TiO_2. This test dust has a particle size range <80µm with 15 - 19% being smaller than 5µm. For the purposes of these tests electrolytically reduced Fe powder cut between 0 - 45 µm, mixed in the ratio 40% Fe to 60% ISO 12103-1 Medium Grade Test Dust by weight has been added to form the contaminant.

EXPERIMENT 1, STATIC WASH OUT – This experiments aims to establish the improved performance of an FM016 centrifuge fitted with a silt retention cone over a standard centrifuge. Firstly a standard rotor was tested as described below and this result was compared with a second rotor fitted with silt retention cone and tested in a similar way. An ingression rate of approximately 0.8mg/L/hr was been estimated for a typical transmission of the size to which two FM016 centrifugal filter would be fitted. This equates to a total contaminant ingress of ≈150g in 1000hr. In this study a contaminant mix of 60% ISO 12103-1 Medium Grade Test Dust cut with 40% electrolytically reduced Fe was used to represent a typical transmission contaminant. The study focused on three levels of contaminant loading 25g, 50g and 100g.

Test Procedure

1. 24 Litres of Castrol CRH30 mineral oil is heated to a controlled temperature of 80°C in the test apparatus whose schematic diagram is shown in figure 10. This is cleaned down to a cleanliness level of better than ISO 4406 17/15 using a PALL Ultipor III 3 µm ($\beta_3 \geq 200$) filter. Particle levels were monitored in this study using a Vickers Target Pro Particle Counter.
2. On reaching the specified level of cleanliness the PALL filter is removed from the circuit and the FM016 centrifuge started with a controlled inlet supply pressure of 5.0Bar (72.5psi) using a closed loop control system to adjust the circulating pump speed.
3. 15g of ISO 12103-1 Medium Grade Test Dust is cut with 10g of electrolytically reduced Fe and added to 1 Litre of oil. This is then added to the sump over a period of 8hr resulting in a contaminant concentration of ≈1g/L of oil. The centrifuge is then left operating until the 5µm particle level is < ISO16 (<640 particles/ml).
4. On reaching the specified cleanliness level the test rig is turned off and left to stand for 8hr. This allows the oil to cool and a proportion of the residual oil (and contaminant) in the centrifuge to drain into the sump under the influence of gravity.
5. After the 8hr standing period, the temperature of the oil is recorded and the test rig turned on. 2, 5, 10, 15, 25 & 50 µm particle levels were monitored by online sampling using the Vickers Target Pro until a 5µm particle level of < ISO16 (<640 particles/ml) has once again been achieved.
6. At this point steps 3-5 are repeated adding a further 25g of contaminant to the sump.
7. On completion of step 6, steps 3-5 are once more repeated, however, 50g of the 60/40 cut contaminant is this time added bring the total amount of contaminant added to the sump oil up to 100g.

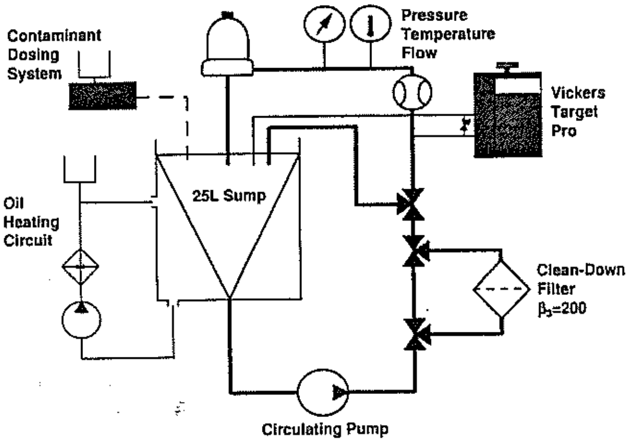

Figure 10. Schematic Diagram Of Test Apparatus For Static Wash Out Evaluation

Comparison Of Static Wash Out With And Without Silt Retention Cone – It is better to interpret the results graphically since trends are easier to see in this way and plots have been produced for the two rotor types tested. Figure 11 shows a time history of sump particle levels >5 and >10mm for the initial test where a standard FM016 rotor was tested and figure 12 shows a similar plot for the centrifuge fitted with the silt retention cone. The test rig and hence the rotor on and off points are also indicated.

On examination of figures 11 and 12 it can be seen that there are two features to observe. Firstly, the level of contaminant wash out attributed to drainage of the rotor while switched off (static wash out). This can be estimated by observing the increased level of contaminant in the sump on re-start of the centrifuge after it's off period. The second feature being the rise in sump particle concentration levels and subsequent clean up time once the rotor has re-started (dynamic wash out).

In more detail, it can be seen when comparing figures 11 and 12 that similar trends exist in both tests. Higher levels of static wash out being exhibited with increased contaminant loading. This is thought to be due to the combined effect of more contaminant in the rotor and slower rotor speed caused by accelerated bearing wear which was also observed during the test. It should be noted that bearing wear in these tests is only an adve effect of accelerated contaminant loading of the system.

It can be clearly seen from the sump contaminant levels, wash out and the resulting clean up time exhibited by the retention cone rotor out performs the standard rotor design especially in reducing static wash out at higher contaminant loading conditions.

Observations – The results indicate that reduced static wash out can be achieved whilst still maintaining optimum performance by use of a silt retention cone in the cleaning chamber of the centrifuge. This cone effectively contains the slump of contaminant when the rotor is not rotating thus reducing the amount that drains back into the sump. Sump contaminant concentration can be seen to be reduced using the silt retention cone by approximately 1 ISO concentration code level, which is significant. However, the silt retention cone does not address the effect of dynamic wash out which can still observed.

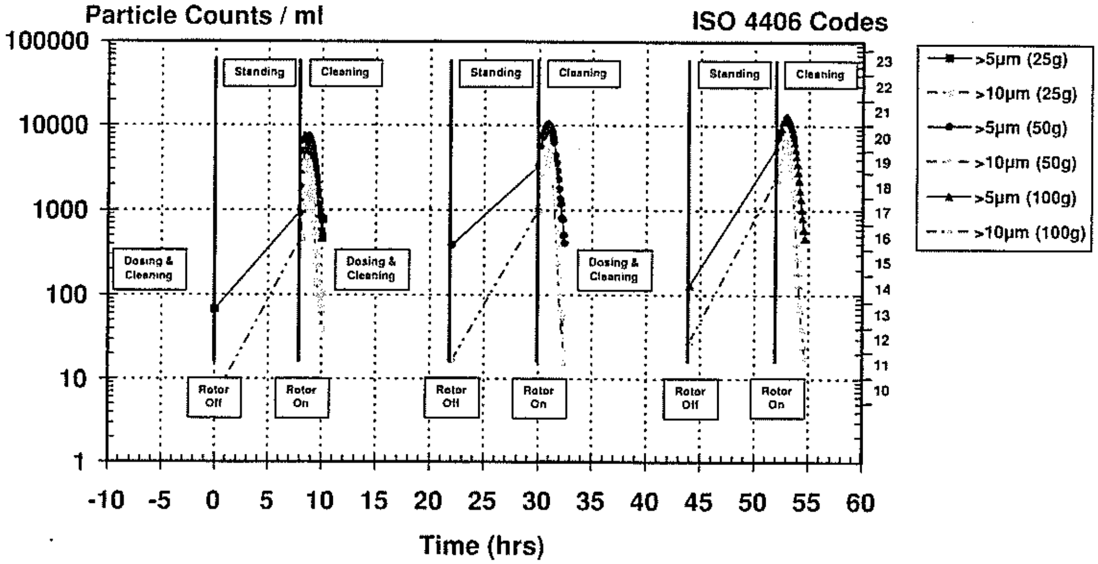

Figure 11. Static Wash Out, Standard FM016 Centrifuge

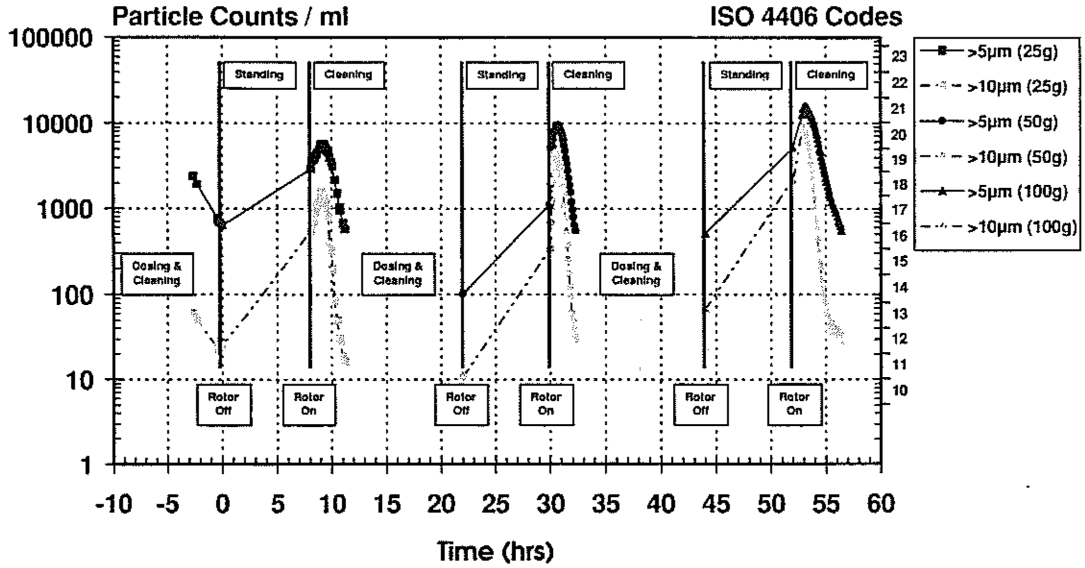

Figure 12. Static Wash Out, FM016 Centrifuge Fitted With Silt Retention Cone

PERIMENT 2, DYNAMIC WASH OUT – The previous experiment was aimed at establishing the static contaminant retention characteristics of an FM016 rotor. The result of this experiment showed how static wash out could be reduced however dynamic wash out was not addressed.

Dynamic wash out occurs when the rotor is restarted from cold and hence the viscosity of the oil is high. This in turn detrimentally effects the speed performance of the rotor lowering it from its normal operating conditions. The effect on contaminant wash out of this highly viscous oil is to entrain contaminant from the rotor back into the sump and since the rotor is not spinning at its normal operating speed the amount of contaminant being removed by the rotor is less than the amount of contaminant being washed out of the rotor, thus the contaminant concentration level in the sump rises. As the temperature the oil increases so its viscosity decreases and hence or speed increases to a point where the amount of contaminant being removed by the rotor equals the amount of contaminant washed out of the rotor. From this point on the rotor then acts as normal and cleans the system.

This second study focused on starting the rotor when the oil temperature was sufficiently high to allow it to operate effectively. In this study we examined an FM016 rotor fitted with a retention cone and compared it with the results of experiment 1. The artificial contaminant used for this test was a mix of 60% ISO 12103-1 Medium Grade Test Dust cut with 40% electrolytically reduced Fe to represent a typical transmission contaminant and three levels of contaminant loading 25g, 50g and 100g were studied, as in the previous experiment.

Test Procedure

24 Litres of Castrol CRH30 mineral oil is heated to a controlled temperature of 80°C in the test apparatus whose schematic diagram is shown in figure 13. This is cleaned down to a cleanliness level of better than ISO 4406 17/15 using a PALL Ultipor III 3 µm ($\beta_3 \geq 200$) filter.

2. On reaching the specified level of cleanliness the PALL filter is removed from the circuit and the FM016 centrifuge started with a controlled inlet supply pressure of 5.0Bar (72.5psi) using a closed loop control system to adjust the circulating pump speed.
3. 15g of ISO 12103-1 Medium Grade Test Dust is cut with 10g of electrolytically reduced Fe and added to 1 Litre of oil. This is then added to the sump over a period of 8hr resulting in a contaminant concentration of ≈1g/L of oil. The centrifuge is then left operating until the 5µm particle level is < ISO16 (<640 particles/ml).
4. On reaching the specified cleanliness level the contaminant test rig is turned off and left to stand for 8hr. This allows the oil to cool and a proportion of the residual oil (and contaminant) in the centrifuge to drain into the sump under the influence of gravity.
5. After the 8hr standing period, the temperature of the oil is recorded and the test rig turned on. Sump contaminant levels were monitored for >2, >5, >10, >15, >25 & >50 µm particle using the on-line sampling technique at intervals of approximately 5 minutes. However, the centrifugal oil cleaner is by-passed through the solenoid valve and oil allowed to flow via a fixed restriction (to give a similar flow rate to that of the centrifuge) back to the sump (see figure 13).
6. When the temperature of the circulating oil reaches 50°C, the by-pass solenoid valve is actuated and the flow of oil is diverted back to the centrifuge. Monitoring of the sump contaminant particle level continues until a 5µm particle level of < ISO16 (<640 particles/ml) has once again been achieved.

7. At this point steps 3-6 are repeated adding a further 25g of contaminant to the sump.
8. On completion of step 7, steps 3-6 are once more repeated, however, 50g of the 60/40 cut contaminant was this time added to bring the total amount of contaminant added to the sump oil up to 100g.

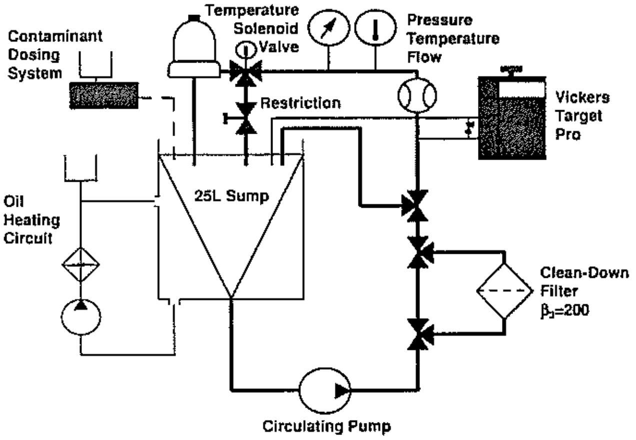

Figure 13. Schematic Diagram Of Test Apparatus For Dynamic Wash Out Evaluation

Comparison Of Dynamic Wash Out With And Without Minimum Operating Temperature Control – Figure 14 shows the sump particle contamination level for particles > 5µm and particles > 10µm as a function of time and contaminant dosing. Figure 15 is the corresponding record of rotor speed and sump oil temperature.

Detailed examination of figure 14 indicates that after cleaning down the contaminated oil to a cleanliness level of ISO16 (>5µm, ISO 4406), at which point the rotor is turned off. There is a sudden rise in the level of sump contaminants as the rotor slows down and contaminated oil drains back into the sump (static wash out). It is assumed that the static wash out continues to rise over the next 8hrs but at a far reduced rate, however, the rate of change of this phenomena was not recorded since it was not considered to be important. The magnitude of static wash out is generally seen to be higher when the test rig is restarted confirming this assumption.

On restating the test rig after the 8hrs off period at which time the oil has been allowed to cool, the level of sump contaminant is once again seen to rise. This is thought to be caused by re-entrainment of particles which have settled out of solution during the turn off period and would also be observed in real life applications.

On reaching an oil temperature of 50 °C the flow of oil is switched back through the centrifuge which quickly picks-up speed (≈8000rpm), some dynamic wash out can be observed at this point before the centrifuge starts to operate efficiently and clean down the oil once more.

Visual comparison of figure 14 with those of the previous experiment figures 11 and 12, clearly demonstrates that by starting the rotor at a an elevated temperature significantly reduces the level of dynamic wash out from the rotor. Dynamic wash out reductions of 34% - 58% are observed for particles greater than 5 µm (depending on contaminant loading condition), and 50% - 72% are observed for particles greater than 10 µm. This equates to a reduction of 2-3 ISO levels when using a centrifugal oil cleaner fitted with a silt retention cone and operated at temperatures higher than 50°C over a standard centrifugal oil cleaner of a similar size.

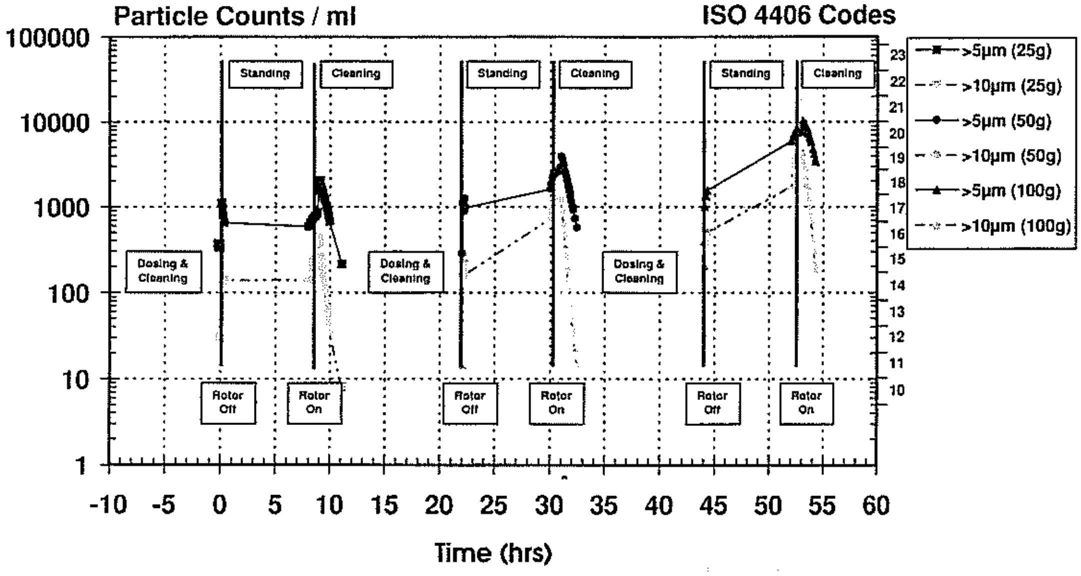

Figure 14. Dynamic Wash Out, FM016 Centrifuge Fitted With Silt Retention Cone Only Operated At Temperatures > 50°C, Sump Contaminant Concentration

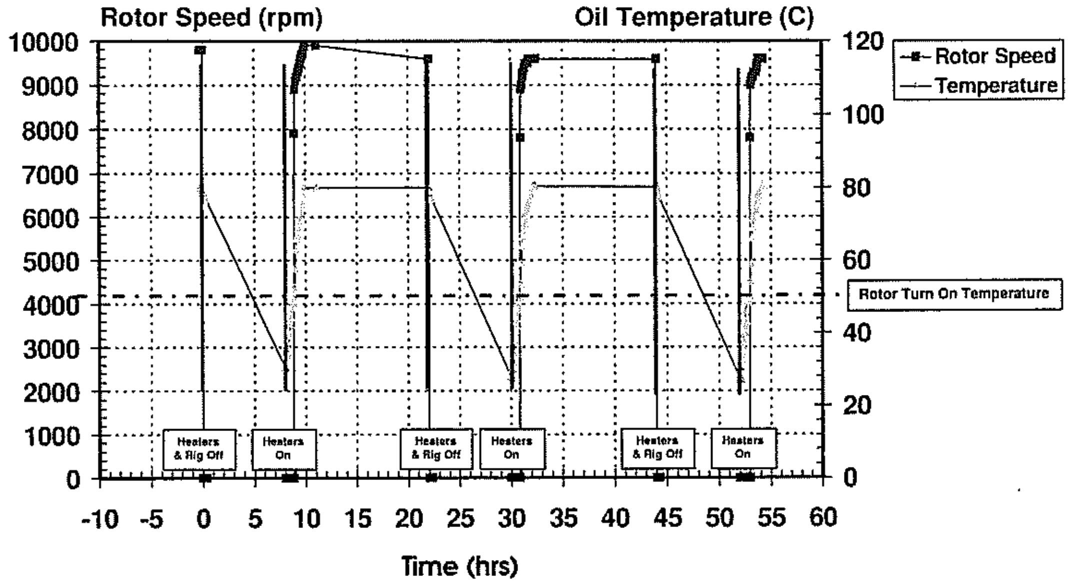

Figure 15. Dynamic Wash Out, FM016 Centrifuge Fitted With Silt Retention Cone Only Operated At Temperatures > 50°C, Rotor Speed And Sump Temperature

SUMMARY

Oil is a vital component of all hydraulic systems it acts not only as a means to transmit power but to lubricate close fitting components. It has been indicated by a number of fellow researchers that the key to component life is the cleanliness of the fluid power system and to these ends the condition of the oil is of paramount importance to the condition of the system. With OEM's striving to increase service life and hence reduce down-time employing by electro/hydraulic actuators with finer and finer tolerances, cleanliness control is the key to success or failure.

The two laboratory experiments illustrated in this paper show that through careful centrifuge rotor design and selection of operating conditions, the level of contaminant wash out can be minimised to acceptable levels. The effect of this on the overall fluid power system will be higher levels of cleanliness hitherto unobtainable within a fluid power system, longer component life and reduced maintenance cost.

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