Paper No. 14—Centrifugal Filtration of Lubricating Oil

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1. INTRODUCTION

Engine lubricating oil filtration is not an exact science. Despite recent advances, detailed understanding of how filters and filtration systems operate is sparse, yet filters are known to facilitate dramatic reductions in engine wear. This paper relates the sizes of contaminants found in used oil to the magnitudes of the oil films between the lubricated components, in order to define the required filtration level in engines. The results of wear tests with oil contaminated by small particles are used to confirm the filtration requirement.

A model of by-pass filtration systems is developed which includes the effects of oil consumption. The amount of contaminant removed is quantified and used to identify further the needs of filtration systems.

A comparison is made of the effectiveness of element and centrifugal oil cleaners, and the way is illustrated in which time dependent effects can impair the long term performance of by-pass systems. Engine tests are described which demonstrate the effectiveness of self powered centrifugal filters.

2. CONTAMINATION AND WEAR

Of the various types of wear present in internal combustion engines, abrasive wear due to contamination is most common and causes the most damage. Most other types of wear are influenced by the presence of contaminants but to a lesser extent. For example, the action of abrasive materials removes thin oxide layers which may otherwise act to inhibit corrosion. Fine metallic contamination can act as a catalyst in the degradation of mineral oils, forming organic acids, and the contaminating particles themselves may be acidic as in sulphurous combustion deposits.

The sources of oil-bound contamination may be summarised as follows:

- Combustion by-products,
- Contamination of the ingested air,
- Dirt found in fuels,
- Bad maintenance,
- Dirt entering through seals,
- Dirt built-in on assembly.

In addition, it is important to recognise that the debris created by wear of the engine components themselves in turn causes further damage; this process is a "chain reaction" and can lead to catastrophic wear failure. In cases of incipient failure it often provides the bulk of the contamination found in the lubricating oil.

The distribution of contaminant particle sizes in used engine oils has been analysed using electron microscopy. The results showed that, above 0.5 μm, the number of particles present varies approximately according to an inverse cube law with particle size. Thus there are many more small particles than large (one 100 μm particle can be broken down into 1000 10 μm particles). Also gravimetric analysis indicated that the mass of contamination found in any band of particle sizes was approximately independent of the mean particle size, provided the band width remained constant.

The high level of contamination found in diesel engine oil necessitates dilution, before optical particle count techniques can be used, and this leads to errors due to additive precipitation. Analysis of contaminant centrifuged from engine lubricating oil, and diluted in N-pentane, has been used to overcome this restriction and confirm the relationship between particle size and quantity. Fig. 14.1 illustrates the distribution of particle sizes from an optical analysis of 1 g of sludge.

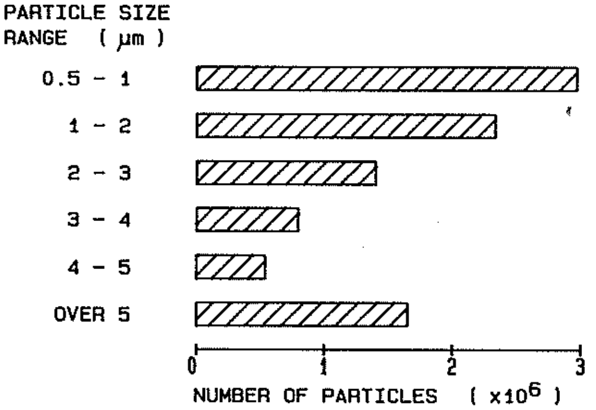

Fig. 14.1 Contaminant particle size and count from 1g of sludge taken from a centrifugal filter fitted to a heavy duty truck engine

Why should the size of particulate contamination be of concern? The answer to this is found in the typical values of oil film thickness between the sliding surfaces of the various engine components. The most critical areas are:

- the piston rings and liners,
- the main and big end bearings,
- the camshaft.

Between a piston ring and cylinder wall, Parker (1) predicted oil film thicknesses varying from 0 to 1 μm. Experimental measurements by Hamilton (2) showed that, even in a lowly rated engine, this film thickness only increased to between 1 and 2 μm. The oil film thickness between a cam and finger follower was predicted by Purmer (3) to vary between 0 and 0.5 μm. Hamilton (4) made measurements which showed camshaft oil films varying between 0 and 7 μm, although at the maximum lift position these were always near to zero. In big end bearings many researchers including Campbell (5) have calculated minimum oil films in the region of 2 µm in medium speed and less than 1 µm in automotive engines.

Abrasive particles which are larger than the oil film thickness interfere with the lubricating process, causing and exacerbating the wear of the engine components. In the case of piston rings, the characteristic wear markings which occur at the top and bottom ring reversal points on worn cylinder bores illustrate this. Purmer (3) demonstrated that maximum cam wear was coincident with the predicted region of minimum film thicknesses, and Ronen (6) showed that radial wear of a circumferential bearing was related to the position of minimum film thickness.

3. WEAR RATE AND PARTICLE SIZE

The measurement of wear rates using graded contaminant sizes in both engines and test rigs confirm the conclusions presented in the previous section. Specifically, where oil films are larger than the contaminant particle size, wear is not significantly affected by contaminant addition, but where the contaminant size is greater than the oil films wear is increased, and the rate of wear is approximately independent of the contaminant size (but closely related to the quantity of contaminant present).

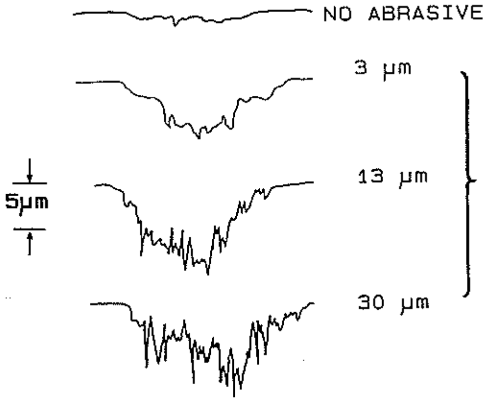

Fig. 14.2 Sections of wear scars from a boundary layer wear rig with different particle sized contamination

Tests were conducted in the laboratories at AE Developments Ltd., using both 'Pin-on-Disc' machines and boundary layer wear rigs with a range of different sized abrasive contaminants. Fig. 14.2 shows cross sections of the wear patterns on samples tested in a boundary layer wear rig in which a pre-loaded pin was reciprocated on test material in an oil bath. In each case the mass of added contaminant was the same. The total material removed is shown in Fig. 14.3 and is approximately independent of contaminant size, although the detailed profiles of the wear scars reflect the different particle sizes. A wide range of material combinations in both this and Pin-on-Disc tests produced similar results. Where wear rates did vary with particle size, this could usually be attributed to the geometry of the leading edge of the sliding component being such as to prevent larger particles from entering the oil film.

Milder (7) also confirmed the relationship between wear, film thickness and contaminant size in engine tests, using thin layer activation techniques. Milder showed that wear in the piston ring area was greater with a mean particle size of 3 µm than with a mean particle size of 30 µm, and almost as great as with a particle size of 10 µm.

Recalling the distribution of contaminant sizes (Fig. 14.1) found in used engine oil, it will be evident that the majority of particles are of a size which could significantly influence the degree of component wear. Many of these particles are abrasive and, in order to minimise their effect, design of the filtration system is critical.

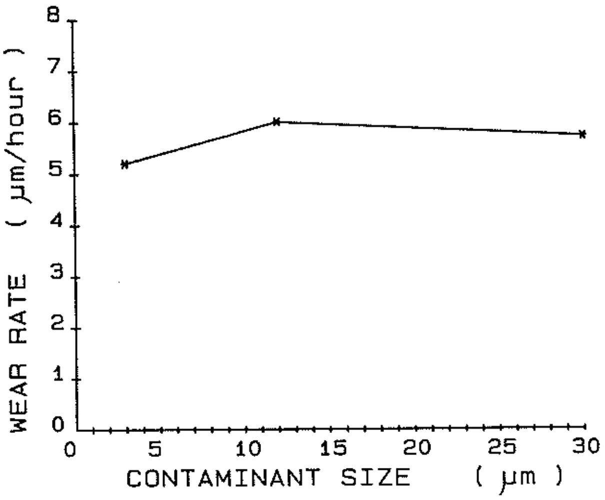

Fig. 14.3 Piston ring wear rate measured in a test rig with different particle sized contamination

4. CONTAMINATION LEVELS IN AUTOMOTIVE DIESEL ENGINES

The rate of insolubles entering the lubricating oil of diesel engines can be classified as normally in the range 5-55 g/MW h. For high speed direct injection (DI) engines 5-16 g/MW h is typical. Indirect injection (IDI) engines have inferior combustion characteristics and normally generate contamination at a rate of 13-55 g/MW h. It should be noted that the rate of generation of contamination in engines is often disguised by high oil consumption, so that the rate at which insolubles enter is always higher than that at which they accumulate in the system.

Experience and practicality have led to a range of recommended maximum contamination levels for engine lubricating oils, normally between 1% and 6% insolubles by weight. For DI engines the recommended levels are normally between 1% and 3%, with 1% often recommended as desirable although in practice rarely achieved. In IDI engines levels between 3% and 6% are more normal, although a desirable level of 3% is frequently recommended by engine manufacturers but rarely achieved. Oil and additive manufacturers more often recommend much higher levels of acceptability, typically in the 4% to 6% range.

It is important to recognise that, although much of the contamination found in engine lubricating oil may not be abrasive, there is inextricable mixing with abrasive material and means of removing it must be able to include the total insolubles present.

In both DI and IDI engines the bulk of contamination is carbon from the combustion process. This can take many forms, and in IDI engines there is a large proportion of very fine (below 0.1 µm) carbon particles. The extent to which carbon is damaging is open to conjecture, but gross contamination levels include much smaller quantities of abrasive material which is known to be highly damaging. Carbon encourages the use of increasing levels of dispersant oil additives, particularly where longer oil change intervals are sought, and these hold small particles in suspension despite the filtration system. In the light of the relationship between small particles and wear it is necessary to question the wisdom of increased levels of dispersant oil additives.

For a typical heavy duty truck engine, with a system capacity of 35 litres, 3% solids by weight is approximately equivalent to 1 kg. A typical truck engine operating at 225 kW for 500 hours would generate between at best 0.6 and at worst 2.2 kg of contamination. Some of this would be lost by oil consumption, but the remainder must be removed by the filtration system if wear is to be contained.

5. FULL-FLOW/BY-PASS FILTRATION SYSTEMS

Engines with force fed lubrication systems generally include a filter between the pump and the lubricated components. Such filters treat the full output of pump to the engine components and are thus termed full-flow filters. As engines have become more highly rated and clearances reduced, so the need for finer filtration has increased and the filters have become more complex. Their ultimate efficiency, however, is limited by the need to avoid introducing flow restriction which might starve components of lubrication. To collect finer particles it is necessary to increase the area of the filter media, but cost and engine size impose limitations on acceptable filter size, and hence on the ability of full-flow filters to remove smaller sized contamination.

In pursuit of finer filtration the concept of by-pass filtration has been introduced, in which a proportion of the oil delivered by the pump is diverted through a second filter and returned to the sump; in this case the full oil pressure drop can be applied across the by-pass filter and this allows finer filtration for a given filter size. By-pass filtration fulfils a subtly different role from full-flow filtration. The primary requirement of full-flow filtration is to protect the engine from damage by preventing potentially dangerous contaminants from reaching the lubricated parts (i.e. large particles capable of causing catastrophic damage). By-pass filtration is a direct attempt to reduce the gross contamination level in the system and hence to reduce long term wear; it is rarely used in the absence of full-flow filtration, although one engine manufacturer uses a hydro-cyclone in place of a full-flow filter.

The remainder of this paper is concerned with by-pass filtration, since this offers the greatest contribution to reduced wear.

6. A MODEL OF BY-PASS FILTRATION SYSTEMS

The principle of by-pass filtration is simple: oil is removed from the lubricating system, passed through the by-pass filter where some of the insoluble contamination is removed, and then returned to the system. The process is continuous whenever the engine is operating. This simplicity lends itself to mathematical modelling, which in turn permits a greater understanding of the fundamentals of by-pass system design.

The contamination in an engine oil is a function of:

— The rate at which contaminant enters,	C	g/h
— The flow through the filter,	F	litre/h
— The system capacity,	V	litres
— The system operating time,	t	hours
— The instantaneous filter efficiency	n	

Contamination level, x g/litre, is a function of C, n, F, V, t and n is defined as the fraction by weight of the contamination which is removed from a small finite quantity of oil passing through the filter.

In practice the rate at which the system capacity is circulated through the filter, N, is a more useful parameter than the flow rate ($N = F/V$).

As by-pass filters collect contaminants so both efficiency and flow rate alter, hence N and n are functions of time. It is reasonable to make the assumption that contamination enters the engine oil at an approximately constant rate. If N and n are also allowed to be time independent (no filter deterioration) then:

$$dx = (C - nNx)\,dt$$

and the contamination in the system x is given by:

$$x = \frac{C}{nN}\left(1 - e^{-nNt}\right)$$

The cumulative efficiency of the system E is given by:

$$E = 100\left(1 - \frac{(1 - e^{-nNt})}{nNt}\right)\%$$

Cumulative efficiency is defined as the percentage by weight of the total contamination entering the system which is removed by the filter, and the equation defines the relationship between the factors which determine the effectiveness of a by-pass filtration system.

For the mass of contaminant with a given particle size in the system two components can be identified, firstly a time dependent part, which describes the probability of any individual particle either passing through the filter or being removed by it, and secondly a time independent part, which describes the contamination level at which, given an infinite operating time, the system will stabilise (assuming nothing else changes in the system).

This stable level is given by $x = C/nN$

Fig. 14.4 shows the variation of contamination level with time for different values of the product of instantaneous efficiency and circulation rate (nN). When the factor nN is high contamination in the system rapidly reaches a low stable level, whereas when nN is low the system takes longer to stabilise at a higher contamination level.

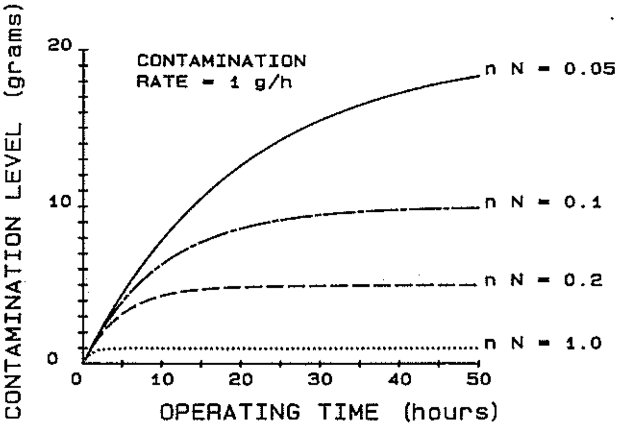

Fig. 14.4 System stabilisation rates for various values of nN (Instantaneous filter efficiency x recirculation rate)

7. PRACTICAL INTERPRETATION OF THE MODEL

The above analysis provides a valuable insight into the mechanics of by-pass filtration systems. Its practical application is difficult because of the complex nature of the term 'instantaneous efficiency', which only has a true value for any one particular particle size and is also likely to change in the presence of other contaminants. In an engine where there is a wide range of contaminants and particle sizes, the effective or gross instantaneous efficiency must be derived from the sum of a large number of the curves shown in Fig. 14.4. It only has a fixed value while the contaminant mix remains constant.

The rate at which oil is circulated through the filter is determined, at least initially, by the system design. The quantity of dirt being removed from the system at any instant is a characteristic of the gross instantaneous filter efficiency and is a function of filter design. Clearly it is possible to have a high filter efficiency with a low circulation rate, or a low filter efficiency with a high circulation rate, with the two systems of equal effectiveness. Gross instantaneous efficiencies of by-pass filters are generally low, and system effectiveness depends on an adequate rate of oil circulation. Efficiencies of new by-pass filters are typically in the range 1% to 5%, exceptionally reaching 10%. System circulation rates are in the range 5 to 25 times per hour.

Gross instantaneous efficiency is a summation over a range of particle types and sizes, which may be influenced favourably by the presence of gums and residues or unfavourably by the presence of dispersant additives. Also, in the above analysis it was necessary to assume no deterioration throughout the life of the filter, which is clearly inaccurate since both flow and efficiency may be subject to considerable change while in service. As contaminants build up on the filtration medium so they occupy the pores through which oil would otherwise pass, so that flow is restricted and pressure builds up, which in turn causes efficiency to change. Typically, truck by-pass filters exhibit flow reductions in the range 50 to 100% during their normal life.

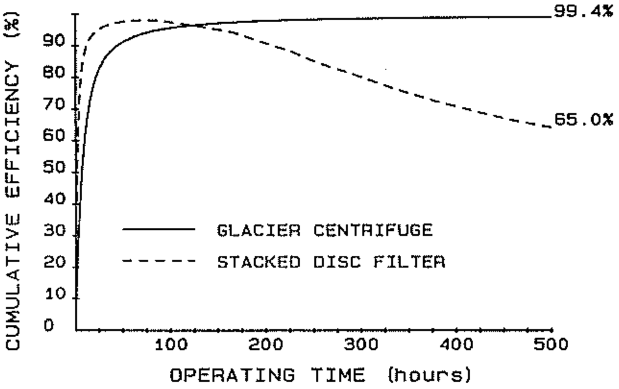

Fig. 14.5 Variation with time of efficiency for a Glacier centrifuge and a stacked disc media type filter with ACFTD contamination (addition rate: 0.25 g/h)

Fig. 14.5 shows laboratory test data on the cumulative efficiency of two filter types, measured over a typical operating period for a heavy duty truck (500 hours) and using a contaminant addition of 0.25 g/h of AC Fine Test Dust with a system capacity of 36 litres. The first is a Glacier self powered centrifugal oil cleaner which had an initial gross instantaneous efficiency of only 3%, but which exhibited little deterioration in either efficiency or flow during the test. The cumulative efficiency of this filter after 500 hours was 99.4%. The second is a stacked disc type. In this the initial efficiency was much higher at 7%, but instantaneous efficiency and flow rate deteriorated during the test so that the cumulative efficiency after 500 hours was only 65%. In the latter case, of course, the effectiveness of the by-pass system is a function of the rate at which contamination enters the system, since it is this which gives rise to the deterioration.

8. BY-PASS FILTER TEST STANDARDS

The curves in Fig. 14.4 exhibit two important characteristics which have serious implications on methods of testing by-pass filters. The first is that gross instantaneous efficiency includes consideration of particles with a wide range of instantaneous efficiencies, therefore the time taken for the system to stabilise approximately during its early life may be a significant part of the filter life. The second effect is that due to deterioration. Referring back to the rates at which engines generate contaminants, it is apparent that for high cumulative efficiencies filters must be able to hold all of the contaminant between service intervals, without exhibiting deterioration.

In establishing test standards for by-pass filters there are therefore two important criteria. Firstly the total contamination added during the test must be representative of the contaminant generated in the engine to which it is to be applied. Secondly the test duration must be of sufficient length to pass through the initial transient effects which are a characteristic of by-pass systems. (Note: full-flow filters are usually tested in a by-pass mode). The cost of testing encourages the use of short term tests which may not fulfil these criteria, and this often leads to erroneous judgments when comparing the effectiveness of different filtration systems.

9. QUANTIFYING THE EFFECT OF OIL CONSUMPTION

There is one further factor which influences the study of by-pass filtration when applied to engines, and that is oil consumption and replenishment. Oil which passes the piston rings and is burnt with the incoming fuel carries with it contamination. Since this oil is normally replaced with new clean oil, it is an additional mechanism by which contamination is removed from the system.

The mathematical model of by-pass filtration can be used to quantify the effectiveness of oil consumption and replenishment as a means of reducing oil contamination, with interesting results. In this case it is necessary only to assume that the consumption/replacement mechanism is continuous; the flow rate is the consumption rate, and since the replacement oil is clean the instantaneous efficiency is 100%. Taking as an example a 500 hour oil change interval Fig. 14.6 shows the relationship between the percentage of contamination removed and oil consumption (expressed as a percentage of system capacity).

Engine design trends are towards reduced oil consumption. Thus this natural means of removing contamination from the oil is gradually disappearing. In quantitative terms this means that the quantity of contamination which must be removed by the filtration system is increasing. It is this mechanism which has led to the increasing use of by-pass filters. Attempting to achieve lower oil consumption without attention to the filtration system will only lead to high rates of wear and necessitate the development of more sophisticated components. Lack of recognition of the need to pay greater attention to filtration leads to high investment in component development in order to achieve durability targets.

European engines currently have oil consumptions in the region of 0.3% to 0.4% of the system capacity per hour, so that 50% to 60% of the contamination entering the oil system during the service interval is removed by oil consumption. In the USA oil consumptions in the region of 0.1% are already common so that only 20% of the contamination entering the system is removed,

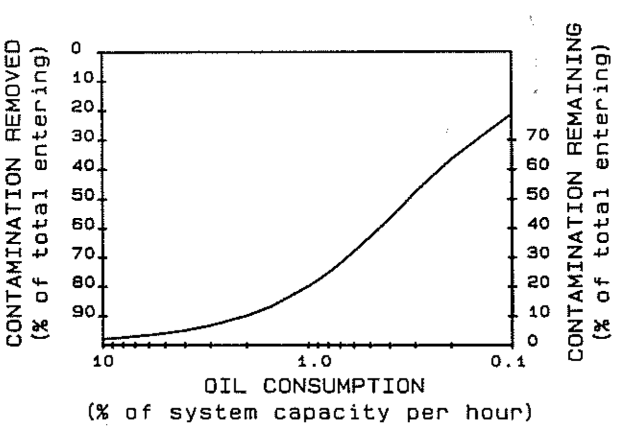

Fig. 14.6 Contamination removed from an engine by oil consumption

leaving 80% to be removed by the filtration system. For this reason by-pass filtration is commonplace in the USA while still relatively new in Europe.

It is interesting to note that the rate of oil consumption in Fig. 14.6 is expressed as a fraction of system capacity, and that the same model can therefore be used to quantify the effect of changes to the engine oil capacity.

Fig. 14.6 is calculated for a typical oil change period of 500 hours, but for other oil change intervals the percentage contamination removed is different. The dependence of the mechanism on operating time is similar to that shown in Fig. 14.4, but in this case a stable condition is not normally reached during the oil change interval. Fig. 14.7 shows how the quantity of contamination removed changes with oil change period for different rates of oil consumption, based on a dirt generation rate of 1 g/h. The mechanism has a greater influence on contamination as oil change intervals are increased. Thus the targets of increased oil change interval and reduced oil consumption compound the problem of oil contamination and necessitate greater attention to filtration systems.

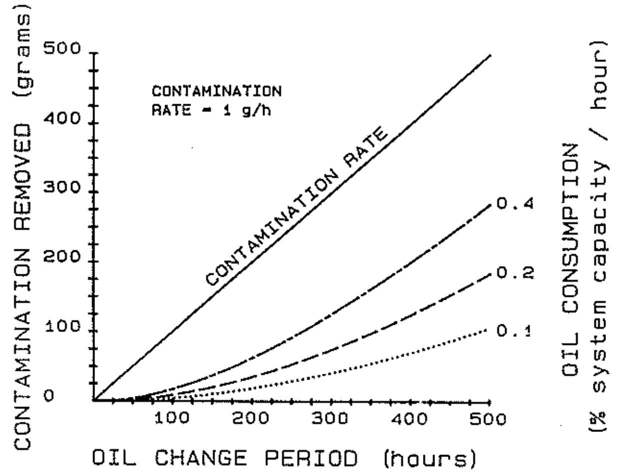

Fig. 14.7 Effect of oil change period on contamination removed by oil consumption

10. BY-PASS FILTERS

By-pass filters are of two types, media and centrifugal. Media devices use the principle of passing liquid through a porous screen to entrap insoluble particles. Pleated paper or stacked fibrous discs are means of maximising the medium area within a given sized container, since the dirt holding capacity of a fixed surface area is limited. Full-flow filters are inefficient at removing contaminant below 20 µm, while by-pass media filters are capable of extending this to 10 µm or at best 7 µm. This is well above the contaminant size range which gives rise to wear but, while the number of particles increases by cube law as particle size decreases, reducing the media pore size only increases the number of pores by square law. Thus media by-pass filters will require significant development if they are to satisfy the demands imposed by longer oil change periods and lower oil consumptions without increases in physical size. Media by-pass filters have demonstrated that significant wear reductions are available from finer filtration (8, 9).

Centrifugal filters are misnamed, and should be called cleaners or separators since strictly they do not use the mechanism of filtration. Mechanically driven centrifugal separators have been used with medium and slow speed engines for many years, but the recent development of lower cost self-powered centrifugal oil cleaners with disposable rotors has made this principle available for use on high speed engines and, possibly, on gasoline engines. Fig. 14.8 shows a typical example of this type of by-pass filtration.

Centrifugal oil cleaners have a number of advantages compared to media filter types. Contaminants are condensed into a dense cake, and for a given size they have a much greater contaminant capacity than media types. This leads to a major benefit in their relative rate of

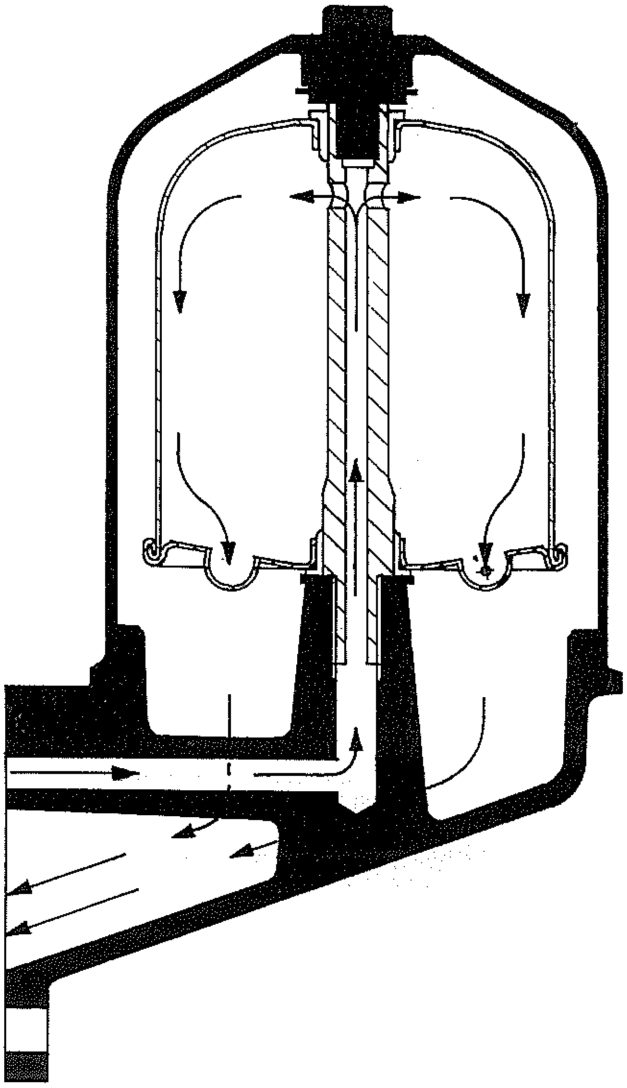

Fig. 14.8 Centrifugal oil separator with disposable rotor

deterioration. Flow through centrifugal oil cleaners does not vary with ageing, and whilst efficiency changes due to an effective reduction in bowl radius as contamination builds up this normally only effects sub-micron particles. Centrifuges are not limited by pore size, and remove particles smaller than 0.1 μm; moreover, centrifuges preferentially remove denser contaminants including the more abrasive materials, especially chrome and iron.

Fig. 14.9 shows the effect on piston ring wear of fitting a by-pass centrifugal filter, of the type shown in Fig. 14.8, to a heavy duty truck engine already fitted with a 20 μm full-flow filter. The results indicate a reduction in wear to one third of the original value, and are typical of gains to be made by the removal of fine contamination from areas where oil films are similarly small.

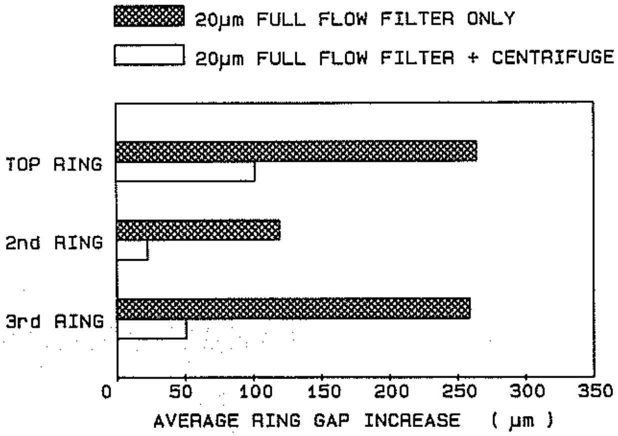

Fig. 14.9 Piston ring wear rates in a 500 hour oil consumption test on a 270 kW diesel engine

11. CONCLUSIONS

Used lubricating oil contains large quantities of particles smaller than 5 μm, which increase in number approximately according to a cube law as particle size is reduced. Minimum oil films in the ring pack, bearing and camshaft areas, however, are in the range of 0 to 3 μm and often below 1 μm. This is considerably smaller than the contaminant particles sizes and laboratory tests have been used to show that, down to at least 3 μm, wear is not dependent on particle size. It is reasonable to conclude that abrasive contaminants which are of magnitudes similar to or greater than oil films interfere with the lubricating process, causing and exacerbating rates of wear. Effective oil filtration is therefore important, and there is a need to provide greater understanding of how filtration systems work.

A model of by-pass filtration systems has been developed which illustrates how reduced oil consumption and extended oil change intervals result in considerably increased contamination levels. It also illustrates that by-pass filter test standards must be based on realistic test periods and representative contaminant levels if they are to be used as a measure of effectiveness.

Conventional media by-pass filters are limited in their ability to remove finer contaminants, and to hold higher levels of contamination without significant increases in size. Centrifugal oil cleaners offer an effective alternative.

PATENTS: Centrifugal filters are the subject of a large number of AE PLC patents and patent applications around the world.

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