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Lubricating Oil & Tear-down Analysis of RECIPROCATING COMPRESSORS

By Ramesh Paranjpey,

Consultant, Pune

Ramesh Paranjpey is a mechanical engineer with an M.Tech in refrigeration from IIT Bombay. He has 35 yearsí experience starting with Kirloskar Pneumatic in Pune in their ACR projects division. Later, he joined Carrier Transicold at Bangalore as their first MD and subsequently as Director Projects in Singapore. For the past 6 years he has worked as CEO of Voltas-Air International Pune manufacturing car air conditioners and mobile defence equipment.

He is a visiting faculty for the Government College of Engineering for graduate and post-graduate courses, and a member of ASHRAE and ISHRAE. He can be contacted at ***pramesh@vsnl.com*** *or on 020-5436142*

In the article that appeared in the January-March 2004 issue we covered reasons for a compressor failure and how to prevent these.

We saw that there are many reasons that can cause damage to compressor components or total failure. If the service technician only replaces the prematurely failed parts, without going into the root cause, the replaced part will also fail earlier than expected.

For identifying the root cause of failure, many times a tear-down analysis of failed parts as well as lubricating oil analysis helps.

Lubricating Oil Analysis

All of us know that oil is required for :

1. Lubrication for rotating and sliding surfaces.
2. Oil acts as coolant and carries away heat generated by friction as well as from the electrical windings of hermetic motors.
3. Oil also dampens mechanical noise caused by moving parts of the compressor.
4. A film of oil protects the internal surfaces of heat exchangers and piping from getting exposed to oxygen and prevents corrosion/erosion of the surfaces.

Lubricating oil analysis done periodically when the plant is in operation gives an early warning about the likely failure which is going to take place and thus helps in preventive maintenance practices and avoiding premature failures. It is a good practice to check an oil sample at least once in a year.

As with human beings, whenever a person falls sick, the doctor analyses his blood, urine and stools sample besides other routine tests. The pathological report helps in finding the cause of his suffering and then appropriate medicines are prescribed to get over the ailment.

Similarly an oil sample retrieved from the compressor helps in deciding whether the plant is operating normally or there is something wrong which could lead to reduced compressor life or premature failure of parts. Corrective steps can then be taken to prevent the same.

The oil analysis helps in identifying the contaminants that have entered the system as well as those generated internally within the system. As the plant continues to operate, these contaminants accumulate in the lubricating oil sump of the compressor crankcase.

The degree of contamination depends upon the operating pressures, temperatures and ambient conditions. It also depends on cleanliness standards observed in manufacturing heat exchangers, compressors and also welding and brazing practices observed during piping and assembling the system.

Once the oil sample is withdrawn from the compressor, it should be sealed in a bottle, which is capable of withstanding the standing pressure of refrigerant since oil sample withdrawn would have dissolved refrigerant in it.

Two types of tests can be performed with these samples:

1. Visual observations
2. Laboratory analysis

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Visual Observations

Odour. The smell of an oil sample, although not reliable evidence, tells us that at least some thing is wrong – an acrid smell indicates possibility of acid being present.

Colour. New, unused lubricant is usually water clear to light straw yellow. Used samples could be dark yellow/ orange/dark brown/ or black.

Yellow colour indicates mild overheating. This overheating could be due to excessive current drawn by the hermetic motor or other mechanical/electric defects.

Orange to dark brown colour indicates excessively high temperatures at which the system is operating or motor burn outs.

Black oil indicates presence of metal particles from compressor castings or from bearings or from cylinder liner wear.

If the black colour is uniform across the sample, it could indicate presence of suspended carbon particles due to motor burn out or excessive overheating which has disintegrated the oil.

If the colour is not uniform and is darker at the bottom and grey at the top of the sample, it would mean heavier metal contaminants concentration towards the bottom.

Laboratory Analysis. Major parameters of the oil sample that can be checked in the laboratory are :

Acidity. Total Acid Number (TAN) is determined by the laboratory to detect presence of strong organic and weaker inorganic acids.

New oil has very low TAN number, less than 0.05. Once the oil has been used its acidity increases due to its being subjected to high temperatures or presence of excessive moisture or both.

Higher acid levels are harmful in mineral oils used for CFC or Ammonia refrigerants. The upper limit of acid in used oil should not exceed 0.5 TAN. If the oil is found to have acidity above this level, it means that the oil should be replaced.

Since POE/PAG oils have been recently introduced for HFC refrigerants, not much data as to maximum allowable acid limits is yet conclusively available, however as a thumb rule 1.5 TAN is a fairly good limit. The higher limit allowable with these synthetic man-made oils is because they contain mostly weaker inorganic acids which are not as aggressive as strong organic acids found in mineral oils used with CFC refrigerants.

When higher acid levels are detected, it is necessary to replace the oil, but it is more essential to find out the reason for the higher acid levels and rectify them before charging new oil.

Moisture. Moisture in the system creates many problems. Ice formation in expansion devices and chemical reactions leading to corrosion are major undesirable effects.

In the majority of installations, a moisture indicating sight glass is used. The colour of the dot in the center changes when moisture is present in the system and this gives a warning signal to the user, indicating the presence of moisture.

Many times a moisture-acid test kit is used to measure the acid and moisture content in the system. Colour change detectors with paper sensing element are used in such test kits. These detectors can be connected to the charge port and will show low, medium and high levels on the paper strip.

To obtain more precise information such as PPM content, laboratory tests are needed.

For new mineral oil, moisture content should preferably be less than 30 PPM but in any case not exceeding 45 PPM. Mineral oils are less hygroscopic compared to POE or PAG oils. POE/PAG oils can easily reach levels of 2000 PPM if kept exposed to atmosphere.

A filter-cum-drier is always used in the system to capture moisture from circulating refrigerant and oil.

If a higher level of moisture is indicated during the sample analysis then it means there is a leak in the system. Many persons feel, if the system is operating with positive low side pressures, the chances of moisture entering the system do not arise. This assumption is not true, since even for a positive suction pressure, because of vapour pressure difference between ambient air and the interior of the system, moisture will penetrate the system.

Other possible sources of moisture in the system are poor assembly practices, using uncapped pipes, or keeping filter drier or other components uncapped for a long duration before use. Moisture can also enter from insulation of motor winding, charging wet refrigerant or wet oil. It is also possible that moisture is generated with in the system when oxygen present in the noncondensables reacts with hydrogenated mineral oils.

Viscosity. One of the main properties of lubricating oil is viscosity. An ideal lubricant would be one which has a viscosity just high enough to prevent metal to metal contact between rotating or sliding surfaces. This would ensure longer compressor life and at the same time ensure minimum frictional losses.

Normally viscosity is indicated in centistokes (cSt at 40°C). As the oil is heated its viscosity is reduced. Similarly when refrigerant dissolves in the oil, its viscosity reduces by at least 2 to 3 cSt.

Depending upon the application and different refrigerants, different lubricating oils are selected. Normally for mineral oils, a viscosity at 40°C ranging between 50 to 68 cSt is recommended for Indian/tropical conditions. These oils normally withstand temperatures up to 140°C and disintegrate beyond this temperature loosing their lubricating properties. System design should therefore ensure that operating temperatures in the system are kept well below this limit.

Different brands of oils are not recommended to be mixed, since each manufacturer adds some “additives” to enhance certain properties of the oil. Some additives added could be :

1. Pour point depressants
2. Floc point depressants
3. Viscosity index improvers
4. Thermal stability improvers
5. Anti wear additives
6. Rust inhibitors etc.

Contaminants. If the oil samples are monitored over a period, increasing levels of iron and aluminum indicates that parts are not receiving adequate lubrication and therefore they are wearing out prematurely. Iron particles presence could also be from compressor bodies, if castings are not cleaned properly or the quality of casting is not up to the mark.

Other elements like phosphorous, zinc, copper silicon, can also be detected with more advanced laboratory techniques.

As can be seen, sampling and analyzing lubricating oil from an operating system is a valuable tool, for troubleshooting and for carrying out preventive maintenance.

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Tear-down Analysis

We shall now look at a systematic way in which teardown analysis for a compressor can be undertaken to detect the cause of failure. Few customers understand why a technician is dismantling a failed compressor. Many think it is unnecessary. It is worth remembering that compressors do not normally fail if they are not subjected to unreasonable operating conditions. There are installations where compressors have been running for more than 25 years and have never failed.

In most of the cases, the compressor is already dead when the service technician visits the site and exactly what happened at the time of failure is not known and therefore needs more investigation.

As the doctor performs a post mortem, to determine the cause of death, on the dead body, a tear-down analysis of a failed compressor also helps many times in determining the cause of compressor failure.

When the compressor stops working, it is not always necessary to remove the compressor from the system immediately, unless it is a sealed compressor. In semihermetic or open type compressors, the compressor should first be isolated from the system by closing the suction and discharge shut off valves.

After isolating the compressor from the system it is necessary to release the internal pressure before opening any part.

Once the pressure is released, the cylinder head bolts could be loosened. In most of the designs a couple of bolts for the cylinder head are provided with longer length, to prevent cylinder head flying off while loosening and causing injury if the internal pressure has not been fully released.

Once the cylinder heads are removed, it is possible to see the gaskets and valve plates, enabling us to visually inspect these for any physical damage or any other abnormality.

Once the compressor is physically removed from the system, the bottom plate, which is of bolted design, can be removed. Many compressor designs have this provision. This exposes the big end of the connecting rods, crankshaft and also allows us to inspect the oil for any contaminants like metal particles, sludge, blackening of oil, etc.

Other parts which can also be removed for inspection without totally dismantling the compressor are oil strainers, suction strainers and crankcase heaters.

If the compressor has been provided with an oil pump, we can remove this also to observe any broken elements, and worn-out parts. Removing the oil pump also exposes the crankshaft bearing end and any wear or scratches can be noticed.

On semi-hermetic compressors, inspection of terminal box, electrical contact terminals can be externally observed and if the end cover is removed, the electric motor is visible and any apparent damage, if it has taken place, can be seen.

All the above observations give us useful data in identifying the root cause of failure without really dismantling the critical parts of the compressor.

We shall now look at the internal parts of the compressor and discuss with the help of observations, as to how to reasonably arrive at the cause of failure

Cylinder Head, Valve Plates & Gaskets. The kind of damages illustrated could be due to two reasons :

- **Flooded start/Liquid slug.** The liquid slug results in abnormal discharge pressures which the compressor is unable to handle and thus the gasket web breaks, releasing this pressure from the discharge to suction side.
  Slugging or liquid stroke taking place is noticed if there is a knocking noise in the compressor. This is due to hydraulic compression, which happens when the compressor is trying to compress liquid. Compressors are designed to handle only gas and any liquid compression would lead to damage of not only valves or gaskets but many other components.
  If the compressor continues to run with a blown gasket, the particular head would run hotter than other heads. This can be felt by touching the underside of the cylinder head.
- A similar effect would also be observed if the compressor discharge shut off valve is not opened prior to starting the compressor and remains closed

inadvertently. Long term and continuous liquid mist coming along with the vapours may not lead to the break down as mentioned earlier, but would cause pitting of parts and the valve plate would show such a pitted surface.

Air or non-condensables in the system cause high discharge pressures and temperatures. This may lead to

overheating. When the discharge line temperature approaches around 140°C, system ingredients begin to break down. The iron in the valves acts as a catalyst, and promotes a chemical reaction between the oil soluble component and the refrigerant. Oil will form a sludge with carbon particles. In time, the carbon particles settle on the valve plate along with the oil as shown in the **Figure 4a**. The hottest parts in the system are valve plates and valve guides. Greater the build-up more will be the damage, leading to increased clearance volume due to build-up of film on the valve plate. Generally the temperature of valves and guides is 15°C to 25°C hotter than the discharge line temperature.

Figure 4a : Sludge and carbon deposits on valve plate.

There are many reasons that can cause a compressor to run hotter than permissible limits. Most common of these is higher compression ratios. High compression ratios are either due to higherthan- allowable discharge pressures or lowerthan allowable suction pressures or a combination of both. Actual and maximum acceptable compression ratios are normally recommended by the manufacturer.

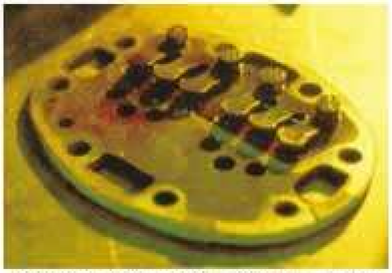

Figure 4b : Varnished stained valve plate.

These vary to some extent from model to model as well as these are different depending upon which refrigerant is used and the type of application.

Low suction pressure is generally more common, leading to higher compression ratios. It is caused by low load, evaporator coil problems, air flow problems, partial refrigerant charge due to leaks developed in the system, improper cut-out settings, frosted coils etc.

Figure 4c : Impressions of ports on valve plate due to deformation.

Higher discharge pressures are due to condenser problems such as choked coils due to dirt, condenser fan problems, air re-circulation or inadequate air flow, noncondensable, higher ambient temperatures etc. On water-cooled condensers it could be scaled tubes, inadequate water flow or higher inlet water temperatures.

The component which suffers accelerated wear due to higher-than-normal discharge temperatures is the suction and discharge valve reeds/plates. The material looses its properties and deforms. Such deformation is observed by markings of the suction port on the valve reeds. The higher discharge pressures also lead to more flexing of the valve than it is designed for. Since this flexing is happening many times per minute it stresses the reeds/plates severely, making them more susceptible to failures.

The non-condensables include oxygen from the air leaked inside the system. Air reacting with mineral oil generates acids and can lead to etching of the surfaces.

On opening the cylinder head, if we notice the valve plate and gasket having more than normal oily surface, it could be due to excess oil in the system. Many times technicians tend to overcharge oil in the system. Oil has no cooling property and hence if refrigerant carries more than necessary oil, the cooling suffers. This is more noticeable in smaller capacity plants.

Many times the oil accumulation on the valve plate or in the system could be due to flooded starts. Every time the compressor pumps liquid refrigerant, it carries oil along with it, which remains behind in the system. Overdesigned systems also have this problem, since there are too many starts/stops. Every time the compressor starts, it carries oil with the refrigerant, but there is not enough time for the oil to go through the entire system and return to the compressor, since by this time the compressor has already stopped due to it's over-designed capacity, tripping on thermostat.

Figure 5 : Oily/Sludge valve plate.

On the other hand, if we find valve plate and gaskets absolutely dry without any traces of oil, it may mean loss of lubrication, due to either inadequate oil or oil return problems due to wrong design of piping, wrong design of accumulator, oil getting accumulated in the system due to wrong designs, or due to low refrigerant charge.

It should be remembered that oil is required for lubrication in the compressor only. Presence of oil any where else is unwanted. The equipment, system and piping design should be such that whatever quantity of oil leaves the compressor, the same quantity should return back to the compressor from the system.

Figure 6 : Dry valve plate.

One of the causes of deformed valves could be that valve plate material is defective or not manufactured properly. This could also lead to valve plate breakage or deformation. It is very rare, but possible.

We have discussed in great detail the effect of overheating, contaminants and lubrication failures as also the effect of liquid slugging, since valve plates are dynamic and delicate parts within the compressor that are subjected to most severe conditions to be encountered any where in the system compared to any other component. Valve plate failures are therefore the most common occurrence in any reciprocating machine compared to any other failures.

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Cylinder Head Inspection. The observations made for valve plates are very similar for cylinder head also, since these components are very near to each other and are subjected to similar pressures and temperatures. The only difference is that the cylinder head is a non-moving part unlike valve reeds.

Figure 7 shows two cylinder heads, one which is brand new and the other which has a sludge build up because contaminants were left in the system due to motor burnout. Motor burnouts are direct results, in most of the cases, of excess heat and will lead to formation of acids and carbonized sludge. It is therefore essential to clean the system thoroughly after the motor burnout problem is attended to.

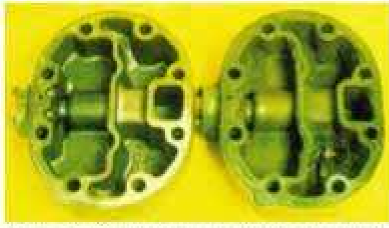

Figure 7 : New and used cylinder head with sludge and caked carbon in discharge area.

Oil Pump and Bearing Analysis. Generally oil pump and oil pump side bearing failures are less frequent because they are the first components to receive oil.

The failure of an oil pump can be attributed in most of the cases to incorrect machining and alignment of oil pump shaft axis and crankshaft axis, if the oil pump is driven off the crankshaft. The adjustment of clearances is very critical and machining tolerances are in microns. While assembling the compressors, utmost care is required in aligning and adjusting various clearances as specified on the drawings.

It is also important to remember that the oil pump is the first component which draws the oil from the crankcase and therefore is the first part to be subjected to contaminant attack. Many failures occur due to contaminants entering/blocking oil passages leading to lubrication failure. A fine mesh cleanable oil strainer at the pump inlet saves a lot of subsequent problems due to contaminants.

After removing the oil pump and observing the bearing head, look for scratches on the bearing surfaces due to contaminants. These scratches are distinct from regular oil retaining grooves and should not be confused as scratches.

Figure 8 : Oil pump analysis.

After removing the oil pump, it is possible to rotate the crankshaft using an allen wrench to see if the pistons are moving with normal resistance. This will save unnecessary opening of other parts.

If the bearing is found seized, then it indicates lubrication failure.

If the pump side bearing is damaged then it could be due to liquid refrigerant present in the oil, because as the oil-refrigerant mixture passes through the crankshaft, the refrigerant will flash off, so that near the end of the lubrication passage the oil will nearly be free from refrigerant and the bearing on the end of the passage will not be damaged.

On the other hand, if the bearing near the pump is found okay but other parts show sign of wear, it indicates that the oil pump is not able to develop enough pressure to overcome system resistance which leads to inadequate flow leading to failure or scratch marks. The higher system resistance could be due to contaminants blocking the lubrication path, or increased clearances leading to inadequate pressure.

Connecting Rod & Crankshaft Analysis. When the discharge valve fails or the head gasket has blown, the pressure on top of the piston continues to remain high. This results in loss of lubrication to the bottom of the small end of the connecting rod, and the gudgeon pin continues to press on the wrist pin on both the upward as well as on the downward stroke. This results in wrist pin bore to wear out making it oblong as shown in **Figure 9**.

Figure 9 : Oblong small end of the connecting rod.

The three deadly enemies of the compressor are liquid stroke, contaminants in any form and heat.

Liquid refrigerant slugging can have a disastrous effect. When liquid enters the compressor, the force that results while trying to compress the liquid refrigerant or oil is extremely high. Pressures of well over a thousand psi can be reached in the cylinder. Compressor parts are not designed to withstand such abnormal pressures and may result in punching holes in the top of the piston, or breaking the crankshaft in two pieces, as if it was cut by a hacksaw blade. Such occurrences are not very common but are possible if liquid stroke is very severe. Normally the weakest part, which is the web of the connecting rod breaks. There are instances when all the connecting rods have broken and compressor crankshaft continues to rotate idly.

Figure 10a : Broken connecting rods.

Figure 10b : Punched hole in the piston.

Figure 10c : Broken crankshaft.

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Piston and Piston - rings Analysis. High discharge temperatures can cause such effect. Loss of lubrication results in faster wearing out of piston rings or cylinder liners or pistons. We have seen earlier various reasons for loss of lubrication. See **Figure 11a** and **11b**.

Figure 11a : Worn out pistons.

Figure 11b : Piston overheating.

Contaminants. In a sealed refrigeration system only dry refrigerant and dry oil is required. Any other solid or gaseous elements present can be called as contaminants. Contaminants are the major cause of compressor wear and failure. The major contaminants are water, moisture, air, non - condensables, debris, dust, chips of copper, aluminum , welding scale, brazing and soldering flux etc. If the pipes before installation are not cleaned internally and have not been kept with ends sealed, contaminants enter the system and stay inside, gradually wearing the parts. Solid contaminants accumulate in the strainer. If strainer is not cleaned periodically, it gets choked and results in bursting the wire mesh due to high velocities. Thus, all the contaminants then enter the compressor and severe damage occurs.

Figure 12a : Choked oil strainer.

Figure 12b : Choked compressor suction strainer.

Copper Plating. Copper plating is the result of a combination of oil used, high temperatures encountered and presence of moisture. The contaminants gradually displace copper from copper surfaces and these are deposited on the compressor surfaces which are at elevated temperatures, such as bearing surfaces. See **Figure 13**.

Figure 13 : Bearing surface turned reddish.

Gradually the thickness builds up on the surfaces reducing the required clearances and could lead to failures. If on opening, copper plating finish on such surfaces is observed, it could be a sign of moisture present in the oil or in the system coupled with overheating. Moisture in the system reacts with refrigerant and oil to form acids and gradually etch the surfaces of the internal parts Even the parts made of glass like oil sight glass have been affected as can be seen from **Figure 14**.

Figure 14 : Sight glass etching.

Motor Failure. When a three-phase motor single phases, one phase remains unaffected and no current passes through it and the entire load is shared by the remaining two phases. Obviously the windings cannot withstand such high currents and may result in overheating and subsequent failure The pattern of failure is shown in **Figure 15**. One phase is shining and bright which is unaffected and the other two phases are burnt.

Figure 15 : Single phasing.

Over heating. In single phase motors, if the selection of a starting capacitor or run capacitor is not proper and if the voltage is also not proper it could result in a failed start. If the compressor fails to start, it could cause a locked rotor situation leading to overheating of the start windings and failure. The overheating can also result from rapid cycling. Each time the motor starts, the current drawn is locked rotor amps. It takes a few minutes of running to get rid of this heat caused by locked rotor current. Frequent cycling causes a build up of heat since the heat from previous start has not been removed.

Figure 16 : Overheating.

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Motor Failure due to Contaminants. Solid contaminants like oil sludge and carbon particles can plug the lubricating passages preventing proper lubrication. The bearing supporting the motor rotor fails. This causes the rotor to drop on to the stator. As the machine continues to run, the metal filings from rotor and stator start rubbing and penetrate the insulation. This leads to shorting of windings and leads to motor failure. The real cause of failure is not due to faulty motor but due to contaminants in the system.

Figure 17a shows stator failure due to pieces of compressor having been lodged in the stator or between the rotor and stator causing eventual motor failure.

Figure 17 : Motor failure due to contaminants.

Figure 17a : Electrical motor stator failure.

Moisture. Moisture as a contaminant has two primary detrimental effects. First it reacts with refrigerant and oil to form acids and also causes freezeup at the expansion valve. The acid in this case has eaten up gradually the terminal block and the compressor has failed electrically. See **Figure 18**.


Figure 18 : Terminal box corroded.

Conclusion

We have seen how the lubricating oil analysis helps in preventing premature failures. We have also tried to cover reasons why compressors and it's parts could fail prematurely and how to arrive at a reasonably correct diagnosis as to the cause of failure to prevent recurrence. More and more in-depth study of failed parts and laboratory analysis would further strengthen the knowledge and expertise of service engineers in promptly rectifying the faults and giving trouble-free long life to the equipment. This feed back to design engineers would also help them to improve on the designs to make better compressors, although today's compressors are far superior in design and quality, and give many years of good service if subjected to proper operating conditions and maintainance.

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