Rotary air compressor lubrication - developing and testing the new generation of lubricants

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Abstract:
Modern rotary air compressors are designed to operate under more severe and extreme operating conditions than their predecessors. These place greater demands on the compressor oil, in terms of maintaining optimum lubricant performance whilst giving a longer oil life.

This paper looks at the key lubricant performance requirements for rotary compressors, and gives examples of how these are tested and met by lubricating oil manufacturers such as The Shell Group (Shell), using the latest base fluid and additive technologies.

1 INTRODUCTION

Compressors are used to compress air or other gases in virtually every type of industry and process. Their lubrication requirements vary, depending on the type of compressor and the gas, and are often very severe requiring specialised compressor oils. Modern rotary air compressors are designed to operate under more extreme operating conditions than their predecessors. These place greater demands on the compressor oil, in terms of maintaining optimum lubricant performance whilst giving a longer oil life.

This paper looks at the key lubricant performance requirements for rotary compressors, and gives examples of how these are tested and met by lubricating oil manufacturers such as Shell, using the latest base fluid and additive technologies, using as examples the recently redeveloped fully synthetic (polyalphaolefin based) rotary air compressor oil, Shell Corena AS, and two market representative oils designated A and B.

2 PERFORMANCE REQUIREMENTS OF ROTARY COMPRESSOR OILS

In a rotary air compressor the function of the oil is to cool & lubricate the compressor components, preventing metal-to-metal contact, and assisting in the air tight sealing of the rotary elements during the compression process. High quality, premium performance compressor oils enable the compressor to operate at maximum efficiency and with minimum risk of equipment failure and associated process productivity loss, over the often extended operational life of the oil. Some of the key lubricant requirements are high oxidative and thermal stability, deposit resistance, anti-wear performance, rapid water separation and air release, low oil volatility/carryover, and low foaming and corrosion resistance. These properties are strongly influenced by the type of base oil used to produce the compressor oil, which can range from mineral oils through to full synthetics such as polyalphaolefins (PAOs) and esters. The American Petroleum Institute (API) categorises these oil types into groups I to V (see Table 1) depending on their composition.

Table 1 – API base oil types

	Group I	Group II	Group III	Group IV	Group V
Saturates Sulphur VI	Mineral Oil <90% &/or >0.03% & =/>80<120	Mineral Oil =/>90% & =/<0.03% & =/>80<120	Mineral Oil =/>90% & =/<0.03% & >120	PAOs	All Base stocks not in Groups I, II, III, IV, such as esters

Historically many compressor oils were made using group I mineral base oils. Today to meet the more severe performance requirements of the latest generation of compressors, most premium performance compressor oils are based on higher group base oils, with their intrinsically higher lubricant performance. For example, with mineral oils the progression has been from conventional less severely refined group I oils to the more hydroprocessed group II and group III base oils. These have reduced aromatic and heterocyclic contents (which are more prone to oxidation and sludge formation than the other base oil constituents) and so tend to be inherently more oxidatively stable (1), they also exhibit a greater antioxidant response when blended with the latest generation of synergistic multi-component antioxidants. Base oils on their own tend to have limitations in the key lubricant areas. Therefore specialist performance enhancing additives such as antioxidants, anti-wear, anti-rust, demulsifiers, and antifoams, are carefully selected by lubricant formulators to extend base oil performance and life in these areas, and to ensure that the lubricant meets and exceeds the demanding compressor requirements. Compressor technology drivers behind these increasingly severe oil performance requirements include, increased free air delivery, higher discharge pressures and operating temperatures, the increasing use of variable speed drives, reduced oil volumes, and increased oil lives.

Rotary compressor oil performance limits are specified by the original equipment manufacturers (OEMs), and by International bodies (such as ISO, DIN, etc). Shell uses these, together with its own exacting performance profiles, and in-house laboratory and compressor rig tests, to fully develop and evaluate its compressor oils in the laboratory, prior to successful field trials and full commercialization. The laboratory (2) and compressor rig tests are designed to simulate the field conditions that a compressor oil will experience such as elevated temperatures, catalytic metals in the presence of water and air, and to prove that the oil is capable of coping with them over its expected service life.

Some of the key rotary air compressor lubricant requirements, their importance, potential field issues and solutions, and how they can be measured are outlined below:

2.1 Laboratory test procedures

2.1.1 Rotating pressure vessel oxidation test (RPVOT, ASTM D 2272-02a)

50 g of oil with 5 ml water is placed in a vessel together with a copper coil catalyst, pressurized with oxygen to 620 kPa, placed in an oil bath at 150 °C and rotated at 100 rpm. The time is then measured in minutes for the pressure to drop by more than 175 kPa.

2.1.2 Gear load carrying (DIN ISO 14635-1)

This uses the FZG spur gear test rig, with special profile gear wheels. It is filled with oil, run at a constant speed of 8.3 m/sec or higher, with a controlled start temperature of 90°C or higher. The loading is raised in stages and the gears inspected at the end of each load stage. The failure load stage is when summation of scoring/scuffing exceeds limits. Results are reported as the first load fail stage

2.1.3 Rust test ASTM D 665-06

To 300ml of oil is added 30 ml of distilled (A) or salt water (B), a cylindrical steel specimen is immersed, and the fluid stirred, whilst being kept at 60°C, for 4 hours (or longer). Rusting of the steel is assessed at the end of test. A fail is the appearance of any rust spot or streak.

2.1.4 Water separation @ 54°C ASTM D 1401-02

40 ml of oil plus 40 ml of water, is stirred for 5 mins (at 82°C for oils >90 cSt at 40°C). The time is then measured in minutes for the separation down to 3ml of emulsion (nearest 5mins) or the Oil/Water/Emulsion heights are measured if this exceeds 30 mins.

2.1.5 Foaming tested by foam sequence I, II, III, ASTM D 892-03

200 ml of oil at 24°C is blown with air at a constant rate for 5 mins, then allowed to settle for 10 mins. The volume of foam is measured at the end of both times (values called tendency and stability respectively). The test is repeated on a second sample at 93.5°C, & then, after collapsing the foam, at 24°C.

2.1.6 Air release ASTM D 3427-03

Compressed air is blown through the oil, which has been heated to 25, 50, or 75°C. The time is measured in minutes to a reduction of entrained gas to 0.2%.

2.1.7 Oil volatility CEC L-40-A-93 (Noack)

65g of the oil is heated to 250°C in an evaporation crucible and a constant volume of air drawn through it for 60 mins, the percentage loss in mass of the oil is determined.

2.2 Compressor rig testing

Shell has an extensive and comprehensive range of compressor types and makes, installed in its compressor oil test facility to reflect those found in industry. The makes include the main compressor original equipment manufacturers, such as Atlas Copco, Ingersoll Rand, CompAir, Kaeser, and Sullair. They are operated under a variety of conditions, to rigorously evaluate and demonstrate compressor oil performance. This paper presents the results from accelerated, high temperature CompAir Hydrovane 705 rotary vane compressor oil tests, developed at Shell to predict expected oil service life. The conditions are a constant oil temperature of 120°C, an air discharge pressure of 7 bar, continuous operation, and with small samples taken on a regular basis for analytical evaluation to determine the condition of the oil.

2.3 Oxidative and thermal stability

Excellent oxidative and thermal stability is an essential performance requirement for the latest rotary compressor oils. It is heavily influenced by both the base oil type and the combination of antioxidants used, as mentioned previously. The consequences if adequate compressor lubricant requirements are not met can be extreme. For example, if a low quality compressor oil that is not sufficiently oxidatively stable is used, then in service, rapid and extensive oxidation can occur. Resulting ultimately in the formation of oil insoluble oxidation products (giving deposits such as sludge and lacquer), and oil soluble organic acids and polymeric species (giving thickened, potentially corrosive oil), which will shorten the life of the oil, and reduce the compressors operational efficiency and service interval. Thus giving rise to costly and time consuming unplanned compressor maintenance and associated loss of process productivity. All compressor oils will degrade in service with time, but it is the rate at which this occurs that can be controlled, by the lubricant developers knowledge of base oil and additive chemistry.

The initial oxidative stability of a fresh oil can be assessed using the rotating pressure vessel oxidation test (RPVOT) time as measured by ASTM D 2272-02a. Lower tier conventional group I mineral based rotary compressor oils can have a low RPVOT of <200 mins for the fresh oil indicating a low initial oxidative stability, while premium tier full synthetic oils such as Shell Corena AS (PAO based group IV) can exceed 2,000 mins demonstrating high initial oxidative stability.

As will be shown later, for a compressor oil to perform well in service, and give a long and trouble free life, it should have a slow and gradual decline in antioxidancy as the oil degrades normally in service. It is therefore the rate of decline of the RPVOT that is more important than the absolute magnitude of the starting RPVOT (3). This rate can be influenced by a number of factors as will be described later.

2.4 Anti-wear performance
Rotary compressors contain moving and contacting components such as sliding vanes, rotating elements and gears, etc. Premium compressor oils are therefore developed to include extreme pressure/antiwear additives, to ensure that wear of such components within the compressor is prevented. Typically the target minimum FZG failure load stage of such compressor oils would be 11-12, indicating maximum wear protection. ISO 32 and 46 grade oils without extreme pressure/antiwear additives typically give low failure load stages of 6, and provide minimal protection against wear.

2.5 Anti-rust
Rusting and corrosion can reduce oil cleanliness levels, promote abrasive wear and sludge formation, increase oil oxidation and foaming, block filters, and can lead to the failure of components. Good compressor oils contain rust and corrosion inhibitors to prevent these issues. However, some are water-soluble and so can be washed out by condensate water leading to the problems above. The remedy is to change to a compressor oil whose corrosion inhibitors will not be washed out by water. Typically rust inhibition is measured by ASTM D 665-06 A/B or an equivalent method. Good quality fresh oils should gives passes in both the A (distilled water) and B (salt water) parts of the test, poorer quality fresh oils may give fails in either A and/or B.

2.6 Water separation
Depending on the humidity of the inlet air, the compression process can result in substantial quantities of condensate water being produced. If the oil does not readily separate from water, this can lead to the formation of stable emulsions, which can restrict the oil flow, lower the oils viscosity and load carrying properties, and reduce the compressor coalescer life. It can also result in increased oxidation, rusting, corrosion, foaming and air entrainment, which will shorten the oils life and reduce its performance, resulting in increased compressor maintenance. Water separation is generally referred to in the lubricant industry as demulsability and is typically measured by ASTM D 1401-02. Values for good quality oils are generally 15 minutes or under, to reach 3 ml or less of emulsion, while poor quality oils can easily exceed 30 minutes with little separation.

2.7 Foaming and air entrainment
Performance problems associated with excessive foaming and air entrainment include, reduced oil filterability and flow, disrupted fluid film lubrication, accelerated oxidation, and cavitation. Chemical problems such as additive depletion, oil carry over, contamination, and oil degradation can cause/contribute to this problem. Air release is typically measured by ASTM D 3427-03, and foaming by ASTM D 892-03. Antifoam additives are incorporated into compressor oils to control foaming. Air release is generally a function of the base oil and cannot be improved with additives, indeed some additives can cause air release to get worse. Foaming values for good quality ISO grade 32-46 fresh oils would typically have

foaming tendency values of 30 ml or less and air release values =/<4 minutes, while poorer quality oils can have foaming tendency values exceeding 500 ml, and air release values significantly >5 minutes.

2.8 Oil volatility/carry over

Oil volatility is an important parameter to consider for compressor oils since (together with foaming) it impacts on compressor oil carry over. High oil volatility/carry over can have a significant HSSE impact, and will also increase the rate and volume of top-up. Typically the Noack volatility test is used to evaluate lubricant volatility. Premium tier compressor oils such as Shell Corena AS have been designed to have low volatility/carry over, with a typical Noack value for the ISO 46 grade fresh oil being <4 % m/m, while a conventional group I based compressor oil with its wider range of molecular structures and volatilities can exceed 11% m/m.

2.9 Compressor testing

Laboratory testing has always been an integral and fundamental part of the lubricant development process. Although a number of these tests can indicate specific compressor oil performance features, to fully assess an oils final performance requires a controlled and thorough evaluation in a compressor test. The reason for this rigor is that some oils can perform well in laboratory tests, but when placed in a compressor perform poorly, producing in the worst cases gelatinous and acidic oils, deposits, and severe wear.

Shell has an extensive and unrivalled compressor test facility, with a wide range of compressor types from the major manufacturers such as Atlas Copco, Ingersoll Rand, CompAir, Kaeser, and Sullair which allows it to thoroughly test and prove its products before they are commercially launched.

This section presents the results from accelerated, high temperature, CompAir Hydrovane 705 rotary vane compressor oil tests used to develop the new, premium tier, full synthetic, Shell Corena AS. This is a PAO based group IV oil, with a unique, patent applied for additive technology (4). Which provides extended oil and compressor life while preventing deposits and wear. The test has been developed at Shell to predict expected oil service life. Under the conditions of the test an oil experiences a significantly increased severity factor, which rapidly ages and degrades the oil compared to the rate which would typically be experienced in the field. This means that if an oil lasts for 1,000 hours in this test, it is predicted to achieve a typical field life several times this value, if the oil discharge temperature is 70-80 °C. The test conditions are a constant oil temperature of 120°C, an air discharge pressure of 7 bar, continuous operation, and with samples taken on a regular basis for analytical evaluation to determine the oils condition. Oil failure criteria limits include kinematic viscosity increase, the change in acid number of the oil, and the differential filter pressure increase.

Figure 1 shows a graph of oil kinematic viscosity (at 40 °C) versus running hours, during Hydrovane compressor tests of the full synthetic Shell Corena AS 46 and a market representative, fully synthetic (PAO based) ISO 46 compressor oil labeled

oil A. As a compressor oil ages in use due to exposure to oxidative and thermal stresses, oxidation will occur. Which can result ultimately in the formation of oil

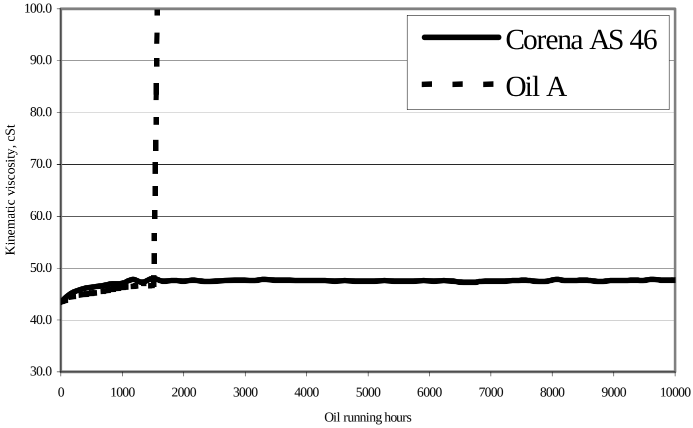

Figure 1 Compressor test – oil kinematic viscosity versus running hours

insoluble oxidation products (giving deposits such as sludge and lacquer), and oil soluble organic acids and polymeric species (giving thickened, potentially corrosive oil), which will shorten the life of the oil, and reduce the compressors operational efficiency and service interval. A good oil is one that exhibits minimal increase in viscosity as it ages. Shell Corena AS 46 exhibits no significant viscosity increase even after 10,000 hours in the compressor, demonstrating its high oxidative and thermal stability (designed into the product by the selection of specialised additives and base oils) over an extended operating life. Oil A although nominally similar, being PAO based, has a different additive chemistry which impacts on its performance. During testing it shows a substantial catastrophic increase in viscosity after ~1,500 operating hours. This indicates that this oil has reached the end of its useful life, and is much less oxidatively and thermally stable. Use of such an oil in a compressor could result in premature failure of the oil and hence the compressor, giving rise to costly and time consuming unplanned maintenance and associated loss of process productivity.

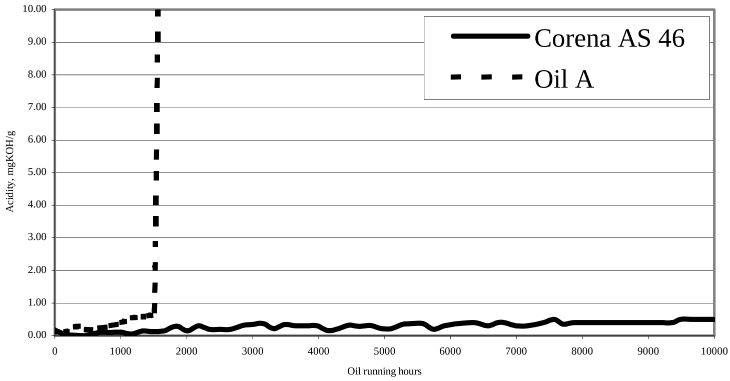

Figure 2 Compressor test – oil acidity versus running hours

Figure 2 shows a graph of oil acidity (mg KOH/g) versus running hours during the same Hydrovane compressor tests of the full synthetic Shell Corena AS 46 and oil A, used to generate Figure 1. Here the catastrophic failure of oil A after only 1,500 hours is shown by the large increase in the acidity of the oil, consistent with the viscosity increase shown in Figure 1. A good oil is one which maintains a low, relatively constant acid value as the oil ages demonstrating long life and stability, such as that shown by Shell Corena AS 46 even after 10,000 hours in the compressor.

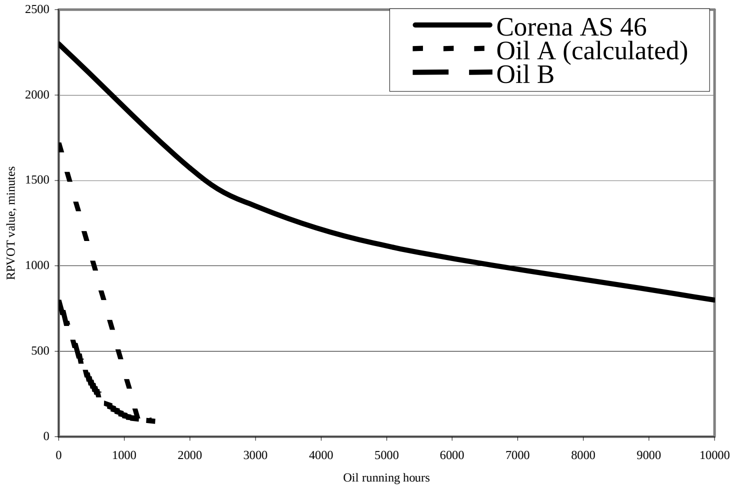

Figure 3 Compressor test - remaining oil antioxidancy by RPVOT

Figure 3 shows oil antioxidancy during Hydrovane testing of Shell Corena AS 46, Oil A (calculated) and Oil B (a market representative group II mineral oil based product). Oil A has a measured starting value of ~1,700 minutes, however this rapidly falls during compressor operation, allowing significant degradation (oxidation) of the oil to occur until after 1,300 operating hours little effective antioxidant remains in the oil, and catastrophic oxidation and failure of the oil occurs (as shown in the previous viscosity and acidity graphs). Oil B shows a slower rate of antioxidant consumption however by 1,500 hours it has reached such a low level that significant oxidation starts to occur (this is reflected by a jump in kinematic viscosity at 40 °C from 46.1 to >54 cSt, and a increase in the oils acidity to > 1mg KOH/g.

As described in section 2.3, for a compressor oil to perform well in service, and give a long and trouble free operational life, it should have a slow and gradual decline in antioxidancy as the oil degrades normally in service. It is therefore the rate of decline of the RPVOT that is more important than the absolute magnitude of the starting RPVOT. The Corena AS curve demonstrates just such a trend, with a significant amount of antioxidant performance (>30%) remaining after 10,000 operating hours providing long term effective antioxidancy. An oils loss of antioxidancy as measured by RPVOT, can be influenced by a number of factors such as, the quantity and type of antioxidant/s used in the oil, the severity of the application, the duty cycle, and the frequency and quantity of oil top-up.

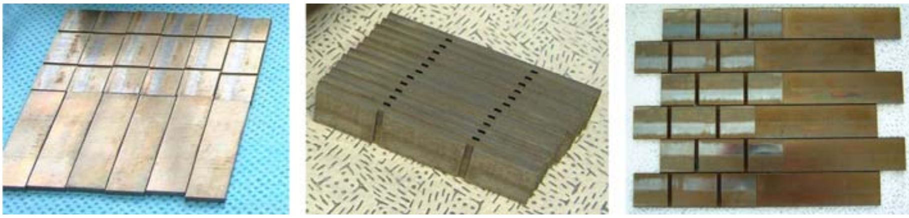

Figure 4 Compressor test – appearance of rotor sliding vanes at end of test for oils A, B, and Corena AS

In addition to monitoring the condition of the oil during the compressor test, at the end of test the compressor is dismantled, and the components examined for deposits and wear, and any other signs of inadequate compressor lubrication. Figure 4 shows the vanes at the end of compressor testing for Oils A, B, and Corena AS 46. Vane wear is assessed by weighing the vanes at the start and end of the compressor test, and dividing by the test running hours to obtain a weight loss per hour. From this it is found that the relative hourly wear rates for Oil A: Oil B: Shell Corena AS 46 are 13:10:1, i.e. Shell Corena AS after running for 10,000 hours provides maximum wear protection (minimal wear of the vane sides or tips) and deposit resistance (no significant deposits were found in the compressor).

3 CONCLUSIONS

Modern rotary air compressors are designed to operate under more severe and extreme operating conditions than their predecessors. These place greater demands on the compressor oil, in terms of maintaining optimum lubricant performance whilst giving a longer oil life. This paper has described the key lubricant performance requirements for rotary compressors such as high oxidative and thermal stability, deposit resistance, anti-wear performance, rapid water separation and air release, low oil volatility/carryover, low foaming and corrosion resistance. Examples have been given of how these are tested and met by lubricating oil manufacturers such as Shell, using the latest base fluid and additive technologies. To optimise an oils performance requires a careful selection of the additive chemical type and concentration. This is due to the fact that while many individual additives can provide strong performance when used in isolation, when combined with other additives to provide well-rounded overall performance, antagonistic chemical effects can occur, resulting in a formulated oil that performs less well than the individual components. The consequences of using such an oil in a compressor are premature failure of the oils performance and increased risk of compressor down time and lost productivity.

Different compressor oils can give widely differing performance levels, therefore careful selection of the most appropriate oil for an application, matching performance requirements with the risk of lost productivity is essential. Environmental considerations for lubricants are also becoming more important with the implementation of sustainable lubricant solutions to reduce potential environmental impacts. For example with Shell Corena AS, beneficial environmental features include, an extended oil life which contributes to a reduction in the rate of consumption of petroleum based products, and the use of metal free (ashless) additives to reduce any impact if the oil is accidentally released into the environment.

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