Use of Oil-Flooded Single Screw Compressors for Hydrogen and other Gases in a 75000 bpd Refinery – Package Designs, Bearing Technology and Practical Experiences

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Introduction

As part of the work to boost production, enhance performance, and enable adherence to new environmental standards, the Lion Oil refinery has taken into service 8 new compressor packages each equipped with an electrically driven single screw oil-flooded screw compressor. Seven of these compressors handle hydrogen-rich process gases, as used in the treating of high-sulfur crude oil, and one installation handles a corrosive refrigerant mixture. It was anticipated that bearing problem might occur based on former experiences gained of compressing such hydrogen-rich gases due condensation issues. Therefore to ensure high reliability the rolling bearing systems have been systematically equipped with state of the art rolling bearings for process gas service[1]. The first units were up and running in mid 2006. Consequently, these compressors and the used bearing systems have seen long term exposure to hydrogen-rich process gases. The paper compares experiences gain on conventional and advanced rolling bearing systems.

Background

The single screw compressor design was selected for the Lion oil refinery installations based on its high flexibility in pressure, pressure ratio and flow rates, and the requirement of simple support and maintenance structures. Thus, offering an attractive combined mix of low CAPEX and low OPEX compared to conventional installations utilizing dry screws or recip compressors.

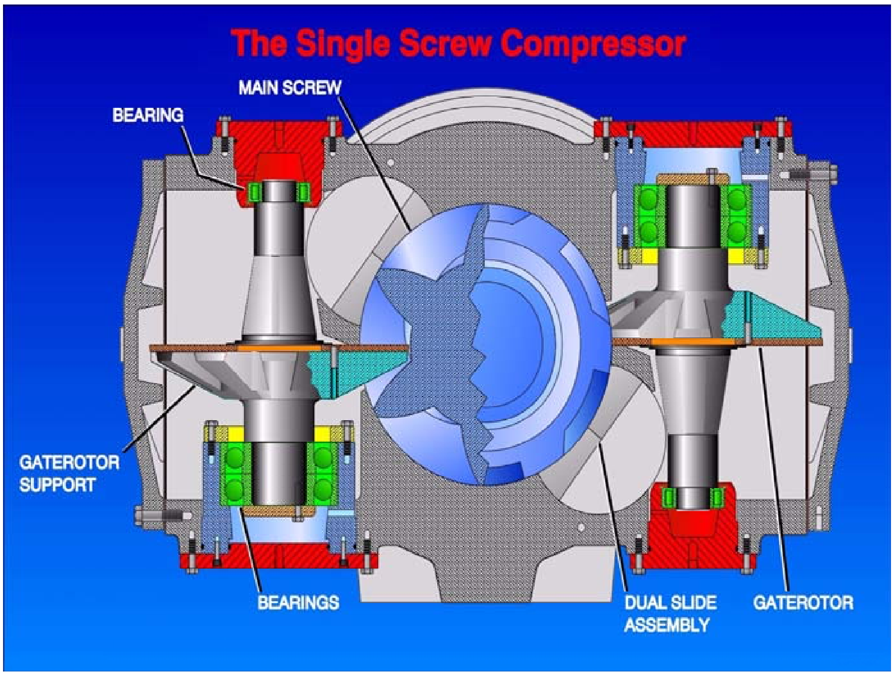

Figure 1. An oil-flooded single screw compressor consisting of one main rotor and two gate-rotors. The compressor has an all rolling bearing arrangement (sketch from a joint Vilter & SCFM presentation).

The basic compressor, utilized in all the Lion Oil packages, was of the Vilter VSG-1801 frame design. It consists of a main single screw and two gate rotors within a compressor housing as seen in **Figure 1**. The main rotor and the two gate-rotors are each supported at one end by two angular contact ball bearings (ACBB), in a face-to-face arrangement, and on the opposite end of the rotor a single cylindrical roller bearing (CRB). In total nine rolling-bearings[i]. The gas is compressed within the six flutes of the main screw rotor by the two gate rotors. The cavities are moving outward in both the axial directions as the two gate rotors are rotating in opposite directions and creating a high number of small pulsations. The axial loads and the radial loads will to a large extent be outbalanced and as a consequence the bearings will see very low loads. In addition all the bearing cavities are under inlet gas pressure & conditions, a feature that reduces the risk to getting condensation in the bearing chambers.

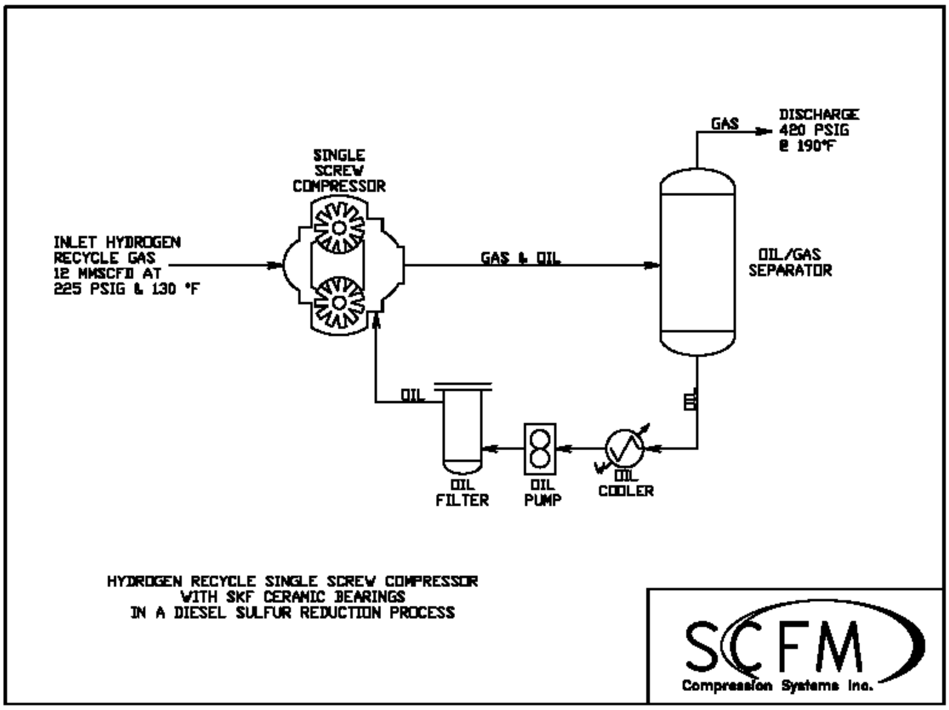

Figure 2. System design for the oil-flooded single screw compressor installations (10-293 main & 10-294 main) within the diesel sulfur reduction process of the distillate unifier.

The process gas goes through an inlet separator to remove liquid and particle impurities before it reaches the compressor package. **Figure 2** shows the process design of the main compressor packages within the distillate unifier unit. These units were the first installations with the single screw compressor within the Lion oil refinery. The lubricating oil is injected into the screws, for lubrication and

[i] Main rotor: Two 85 mm bore size ACBBs and one 85 mm bore size CRB; Gate-rotors: Two 75 mm bore size ACBBs and one 45 mm bore size CRB, on each rotor.

cooling, and the same oil is used to lubricate the rolling bearings. An oil separator recovers the lube oil from the gas stream, which after cooling and filtration is re-injected into the compressor. The process designs of the other units within the refinery are similar. In summary, a process set-up quite similar to the one as used for oil-flooded twin screw compressors, but only one oil injection line is applied instead of three [1,2]. Seven of the installations are handling hydrogen-rich gases and one is used as a back-up installation for a refrigeration cycle (**Table 1**). The refrigeration cycle is normally handled by one dry screw in combination with a centrifugal compressor. All the compressors today are equipped with bearings utilizing ceramic rolling elements of SKF bearing grade silicon nitride and rings of a martensitic super-tough stainless steel (AMS 5898, SKF hardening specification) with a high-nitrogen content. As for compression and running conditions these are quite different between the installations and for the two cases to be discused in more detail the design values are given in **Table 2**.

Table 1. Oil-flooded single screw compressor installations within the Lion oil refinery.

Compressor ID	Compressor frame[1]	HP[2]	Main screw RPM[3]	Process	Gas type
10-293 Main	VSG-1801	800	1800	Distillate unifier	Hydrogen rich[4]
10-294 Main	VSG-1801	800	1800	Distillate unifier	Hydrogen rich[4]
East 1	VSG-1801	800	1800	Hydrogen plant	Hydrogen rich[5]
East 2	VSG-1801	800	1800	Hydrogen plant	Hydrogen rich[5]
East 3	VSG-1801	800	1800	Hydrogen plant	Hydrogen rich[5]
West 1	VSG-1801	800	1800	Hydrogen plant	Hydrogen rich[5]
West 2	VSG-1801	800	1800	Hydrogen plant	Hydrogen rich[5]
C	VSG-1801	800	3550	Alkylation and gas unit	Refrigerant and acid[6]

[1] VSG-1801 use a main screw size with an outer diameter of 350 mm (13.8”)
[2] All on electric drive.
[3] Gate-rotors are at 6/11 speed of the main screw.
[4] Case history I: Hydrogen 65%; Methane 20%; Ethane 6%; Nitrogen 4.5%; Propane 2%; Water vapor 1%; N-Hexane 0.5%; Carbon Dioxide 0.4%; N-Butane 0.15%; and Hydrogen sulfide 0.01%.
[5] Case history II: Hydrogen 60-80%.
[6] Case history III: Isobutane 80% (R-600a); Propane 12%; N-Butane 5.5%; Ethane 2%; Methane 0.7% + unspecified content of sulfuric acid contamination + condensing water at start and stop.

Table 2. Compression conditions for the two main studied process installations within the Lion oil refinery.

Compressor ID	Inlet pressure	Inlet Temp.	Outlet pressure	Outlet temp.	Comments
	psig (barg)	^{0}F (^{0}C)	psig (barg)	^{0}F (^{0}C)	
10-293 Main	225 (15.5)	130 (54)	420 (29)	190 (88)	Case I: High flow, Low pressure increase
10-294 Main	225 (15.5)	130 (54)	420 (29)	190 (88)	
C	8 (0.5)	55 (13)	100 (7)	212 (100)	Case III: Low flow, High pressure increase

Case History I: Bearings to the main compressors of the distillate unifier installations (hydrogen-rich gas).

The distillate unifier installation consists of two main compressor units with one running 24/7 and the second one in idle mode to give a 100% redundancy capacity if required. Each of the single screws replaced the hydrogen loop of one vintage recip compressor in dual hydrogen and net gas[ii] service. It can be noted that the recip loops each had four rod packing seals exposed to discharge pressure, whereas the single screw has only one mechanical seal (rotating carbon/steel) exposed to suction pressure. Thus the single screw compressor significantly reduces gas leakage into the environment when in service.

The installations were originally meant to take alternative turns of operation by switching responsibility every 2^{nd} week. The working unit handles 12 MMSCFD hydrogen-rich process gas (65% hydrogen, see **Table 1** for details) which is feed into a Vilter 1801 compressor at 225 psig (15.5 barg) and compressed 420 psig (29 barg). The compression causes a temperature increase of the gas stream from about 130°F (54°C) to 190°F (88°C).

The lubrication and cooling of the compressor's screws and bearings are done by 150cP polyglycol oil. The oil has anti-corrosive additives added and is filtrated by a 12-micron filter before being injected into the compressor at a temperature in the range of 140°F (60°C) to 160°F (71°C). The oil is re-circulated with lighter condensates and solid particles meant to flow with the main process gas stream. However, it is always a risk that condensation of liquids such as water and light hydrocarbons occurs at the end of the compression cycle and gets into the lube oil. In addition, these condensed liquids and the lubricating oil could become contaminated with brines, acids, mercury compounds, particles etc, or saturated with in water soluble process gases such as hydrogen sulfide and carbon dioxide.

It was anticipated that the bearing problem might occur based on former experiences gained of compressing such hydrogen-rich gases. However, due to a tight design and installation schedule it was decided to make the bearing conversion in three steps as the state-of-art bearings at that time had quite long lead times. The long lead times were caused by limited availability of stainless steel rings and the large ceramic cylindrical rollers for the main screw:

- **Step 1.** Install the compressors with all bearings in conventional (AISI 52100 type) all-steel bearings (first installed June 2006);
- **Step 2.** Upgrade all bearings, except the lowest loaded main cylindrical roller bearing, with super-tough stainless steel rolling bearings with ceramic rolling elements and glass fiber reinforced PEEK cages (converted in December 2006); and

[ii] Each of the net gas loops were replaced by another smaller single screw compressor, not discussed in this paper.

Step 3. Upgrade also the remaining main cylindrical roller bearing with super-tough stainless steel rolling bearings with ceramic rolling elements and glass fiber reinforced PEEK cages (replaced in end of 2008). All bearings converted.

This had the unexpected, but positive, side effect that it was possible to compare the resulting running behavior of the three different bearing systems.

The Step 1 installations proved that the compressor systems worked well but, as expected, a significant number of bearing failure occurs within a short period of time (<1000 hours of running time). Typically the bearings had a hydrogen failure mode as seen in **Figure 3A**. In summary, the typical bearing damages seen were: Spalling (hydrogen cracking); Dulling of raceways and rolling elements (poor lubrication e.g. low viscosity from oil dilution); Scoring of rollers (particle contamination and/or poor lubrication); Contact corrosion marks (standstill in corrosive environments); Staining (corrosion); and Fretting corrosion on outer bearing surfaces (normally a fit issue but probably a secondary cause or enhancements due to the corrosive environments).

The Step 2 level confirmed that by using the advanced bearing system it was possible to achieve significant improvements in bearing life especially on the thrust bearings (**Figure 3B**). But in the end, the single non-upgraded main radial bearing, for the main rotor, did become the weak link. In this particular case the main radial bearing failed after about 8000 hours (**Figure 4**).

Figure 3A. Steel inner ring (conventional AISI 52100) from a thrust bearing used on the main rotor with the raceway spalled (hydrogen attack) and frosted raceways (poor lubrication). Less than 1000 hours in service.

Figure 3B. Super-tough stainless steel ring (AMS 5898) from a thrust bearing in hydrogen rich service. About 8000 hours of service (some light stains).

The Step 3 upgrades have so far proved to be very reliable and are running in the excess of 14 000 hours with all bearings converted to the high standard with stainless steel bearing rings and ceramic rolling elements. In summary, each of the two compressors running on advanced bearings have had such installed in excess of 3 1/2 years with or without the main CRB converted.

Figure 4. A conventional cylindrical roller bearing after 8000 hours in hydrogen-rich environment. The glass fiber reinforced polyamide cage was destroyed and the conventional steel rollers were blackened, corroded and deformed.

Case History II: Bearings for the hydrogen plant.

These five compressor installations in two different parts of the hydrogen plant are running smoothly on a mixture of Step 2 and Step 3 bearing arrangements. All will in due cause be converted to the Step 3 level.

Case History III: Bearings and single screw compressor in combined refrigerant and sulfuric acid service

This is the latest installation done at the Lion Oil refinery with the single screw replacing a vintage recip backup compressor. It is by far the most demanding of the installations and has unusual conditions for a closed loop system. This as the Isobutane refrigerant (R-600a) in the closed loop picks up contamination in the form of sulfuric acid. It was therefore decided from the start to install super-tough stainless steel bearings with ceramic rolling elements in all bearing positions. This single screw, the C compressor, is the back-up compressor for an installation normally utilizing two compressors, a dry twin-screw combined with a centrifugal one.

The compressor was designed to work under shorter periods as the back-up unit, as the service was considered to be very severe. This has been confirmed as the refrigerant seems to clean exposed metal surfaces very well and leave these surfaces prone to attack by the sulfuric acid if condensed water is present. Indeed, the single screw did initially see severe etching on the rotors and bearings, as seen in **Figure 5**. These etched patterns on the rotors were created in less than 100 hours of service after which the compressor was exchanged. It can be noted that the compressor did see a high number of start and stops under this short period of service. These start and stops did cause condensation of water to occur that significantly enhanced the etching effect of the various compressor components including the rolling bearings.

However, the running condition of the compressor has been significantly improved by utilizing a customized compressor oil from Summit with selected anti-corrosion additives. But it is believed that the best effect to reduce the corrosion problem has been gained by avoiding start and stop sequences that cause condensation. In fact, the C compressor has been running continuously in excess of 2000 hours without problem and as such, working as the main compressor instead as the back-up unit.

Figure 5. Etching of the main single screw rotor after being exposed to severe refrigerant - sulfuric acid - water conditions for a 100 hours running period.

Summary

The significant life effects of using rolling bearings in state-of-art advanced rolling bearing materials can be summarized as seen in **Table 3**. The experience also shows that further increases in life can be achieved by optimizing the selection of lubricant and running conditions i.e. by avoiding condensation and standstill periods. The “Step 2 upgrade” does increase the life significantly but in the end the weakest link of the bearing systems, the non-converted, main cylindrical roller bearing, fail as shown in **Figure 4**.

Table 3. Summary: Upgrade steps and the effects on service-life.

Upgrade	**Approximate service-life of bearings in compressor installations**[1] **10-293 main & 10-294 main** Hydrogen-rich service (normal process gas service)	 **C** Refrigerant & sulfuric acid service (extreme process gas service)	**Comments – Bearing systems**
Step 1:	< 1 000 hrs	N / A	All bearing rings, rolling elements & cages in conventional bearing materials[2].
Step 2:	< 8 000 hrs	N / A	All bearings converted[3] except the main cylindrical roller bearing[2] (**Figure 5**).
Step 3A:	> 2-4 years	< 100 hrs[4]	All bearings converted[3].
Step 3B:	N / A	> 2000 hrs[5]	All bearings converted[3] + Optimal selection of anti-corrosion package for the lube oil & reduced exposure to condensing liquid water

[1] Installed time.
[2] AISI 52100 bearing grade steel and glass fiber reinforced polyamide cages.
[3] Rings in SKF super-tough stainless bearings steel (AMS 5898), rolling elements in bearing grade silicon nitride ceramic and glass fiber reinforced polymeric PEEK cages.
[4] Severe damage on rotors & damage on bearings.
[5] Still in service.

Experiences and recommendations gained:

- **Viable compressor alternative:** Single screw oil-flooded compressors can be used in refineries to handle hydrogen-rich process gases if the rolling bearings applied use well selected and defined state-of-art rolling bearing materials.

- **Low CAPEX and OPEX:** Such a compressor installation may offer economically (lower installations costs), service (simpler and cheaper) and process wise (greater flexibility) better alternatives to more conventional alternatives such as recip or dry screw compressors.

- **Process gases:** It is possible to utilize these type of compressor installations in other gases. Experiences show good behavior in both severe sour and acid gas environments for oil-flooded screw compressors.

- **Boosting recip compressors:** This type of oil-flooded screw compressor installations can be utilized to simplify and reduce sizes of recip installations e.g. for various re-injection projects.

- **Continuous running favored:** To fully utilize the capabilities of such compressor installations it is recommend to adjust and tune running schedules and process conditions e.g. by running the compressor as continuously as possible to avoid standstill periods combined with water condensation.

- **Purging and flushing:** At shorter stand still periods the compressor should be purged by either nitrogen or sweet gas. At longer stand still periods the oil systems should be flushed by a cleaning agent or at least the oil should be changed at the beginning of the period in addition to the purging.

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References

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