# HIGH PRESSURE OIL-INJECTED SCREW GAS COMPRESSORS (API 619 DESIGN) FOR HEAVY DUTY PROCESS GAS APPLICATIONS

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## ABSTRACT

Oil-free screw compressors have been used for process gas application since the 1970s. Oil-flooded screw compressors have been used in many process related applications since the 1980s. Inclusion of oil-flooded screw compressors into API Standards (API 619, 1997) and with its expanding role into process compression applications, makes it necessary to present the authors' experiences and share their acquired know-how.

Higher reliability, lower maintenance costs, no pulsation, no extensive foundations, lower operational costs, lower initial costs, and many environmentally friendly qualities are some of the basic attributes of an oil-flooded rotary screw compressor. Those attributes are resulting in a significant demand for such machines, primarily as an alternative to reciprocating compressors.

## INTRODUCTION

The purpose of this paper is to present the experiences gained in using oil-flooded rotary screw compressors in process applications at pressures up to 900 psig. Emphasis is on the growing market as a replacement for reciprocating compressors and the inclusion of such machines in the latest edition of API 619 (1997).

The overall outlook of compressor types and their applicable ranges have gone through a revolutionary change in recent years with screw compressors staying continually at the cutting-edge.

## HISTORY

In the late 1950s, a Swedish company developed the oil flooding technique in a screw compressor and perfected the rotor profile to achieve high efficiency. They then licensed compressor manufacturers in the USA, Europe, and Japan to manufacture these compressors and collect royalties. Since the oil-flooded screw compressors have characteristics of both rotary (centrifugal) compressors and positive displacement (reciprocating) compressors, such machines found rapid acceptance in the petrochemical and gas processing industries.

In 1975, API 619 was introduced to specify a screw compressor. This first edition of API 619 looked only at oil-free screw compressors. During this period, oil-free screw compressors were applied in many unique applications such as butadiene, styrene monomer recycle gas, linear alkyl benzene, soda ash, etc. Most of the applications are sensitive to dust and liquid and are likely to form polymers if in contact with oil. In many cases, water injection was used to control the compression process.

In the 1980s, oil-flooded screw compressors started appearing in process gas applications. A slide valve in oil-flooded screw compressors offered a stepless turndown to 15 percent and, as a result, part load performance improved greatly. Around the same time, cogeneration started to take off with gas turbine boosters becoming necessary in more and more applications. The oil-flooded screw compressors are very suitable for these applications, since the requirement of the fuel gas booster fits very well with characteristics of oil-flooded screw compressors, i.e.,:

- Suction pressure fluctuations
- Gas turbine load fluctuation, i.e., flow rate fluctuation
- Unstable gas composition (typically natural gas)

Also, this fuel gas booster application requires economical operation, and the oil-flooded screw compressor with a slide valve as an unloader can provide significant power savings.

In the early 1980s, oil-flooded screw compressors were finding their way into light gases such as helium and hydrogen. Lower influence of changing molecular weight made such compressors particularly suitable for hydrogen pressure swing adsorption (PSA) compressors. On helium and hydrogen feed compressors, stringent oil carryover requirements made it necessary to introduce activated charcoal absorbers in the oil management system. Carbon dioxide compressors for the beverage industry switched to oil-flooded screw compressors with an oil removal system down to 10 parts per billion (ppb) by weight.

In the 1990s, oil-flooded screw compressors became larger and larger with several applications not only involving multiple compressors on common lube oil systems, but the compressor flame size became larger. In the late 1990s and early 2000s, high pressure compressors started to find their way into fuel gas boosters and petrochemical applications. Currently, machines up to 900 psig with the next generation up to 1400 psig are in production.

## GENERAL DESCRIPTION OF OIL-FLOODED SCREW COMPRESSORS

A cutaway drawing of a typical oil-flooded screw compressor is shown in Figure 1. There are two rotors inside the casing of an oil-flooded screw compressor. One rotor is referred to as male, and the other rotor is the female.

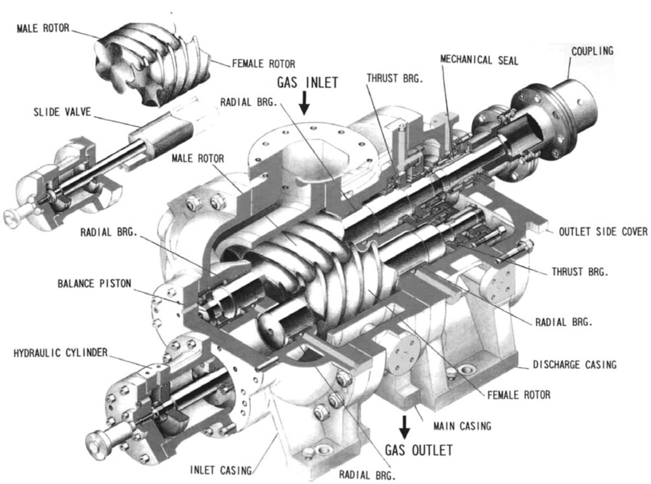


*Figure 1. Typical Cutaway of Oil-Flooded Screw Compressor.*

The male rotor drives the female rotor by contacting each rotor surface via an oil film. The male rotor is driven by a directly coupled two-pole or four-pole electric motor. A gear unit is typically not used since the tip speed of the oil-flooded screw compressor is in the proper range by nature. In other words, the rotating speed of the rotors is the same as electric motors, so the rotors are considered as a rigid shaft, i.e., there is no critical speed issue on the oil-flooded screw compressors.

There are journal bearings inside the rotor chamber, and sleeve types are typically used (especially for high pressure applications).

Thrust bearings are located on the outer side of the journal bearings, and tilting pad types are typically used. Since oil is injected into the rotor chamber, there is no seal between the bearing and rotor; however, one mechanical seal is located at the shaft end.

Oil injected directly into the rotor chamber, bearings, and mechanical seal acts as a lubricant, sealant, and coolant in the screw compressor. The oil is then discharged with the gas through the compressor discharge. The discharged oil and gas are separated in the bulk oil separator located downstream of the compressor discharge.

Oil contained in the bulk oil separator is circulated in the compressor lube system.

A slide valve as unloader is located in the compressor just beneath the twin rotors and is used to adjust the inlet volume. The inlet volume of the compressed gas can be adjusted by moving the slide valve, which is actuated by a hydraulic cylinder. A schematic diagram for an oil-flooded screw compressor is shown in Figure 2.

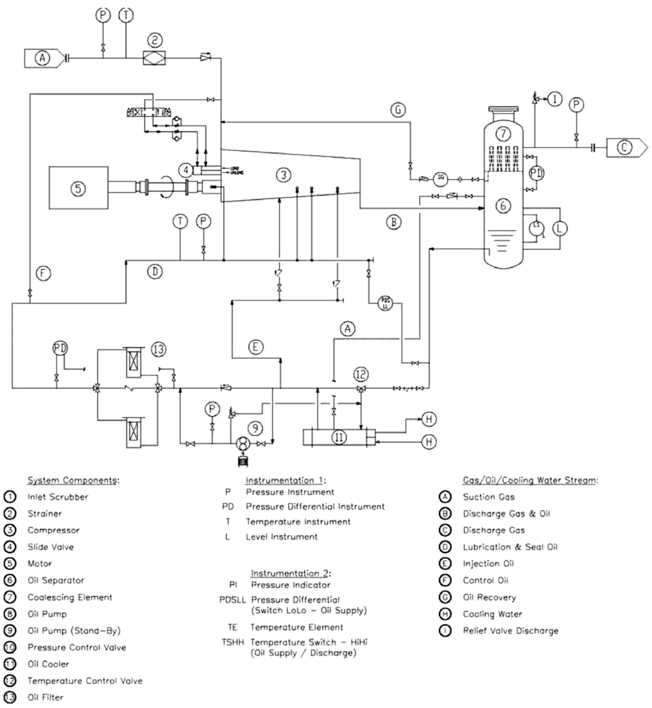


*Figure 2. Typical Schematic Diagram for Oil-Flooded Screw Compressors.*

Compressor lubricant oil is present in the process side (as seen in Figure 2), so the lube oil selection is very different from other types of machines. The bulk of the oil is separated in the bulk oil separator, but a secondary coalescing oil separator may be used as an additional separator. Separated oil is then circulated in the lube oil system of the compressor. The lube oil system consists of compressor lube lines, oil cooler, oil filters, and oil pump. The oil pump may be double or single configuration. The design of a single pump system is used for oil-flooded screw compressors when the pump is required only during startup. After the compressor starts, and discharge pressure is established, oil can circulate in the system by gas differential pressure from the discharge side to the suction side.

Oil-flooded screw compressors have many advantages. Below is a list of some of the main advantages of the oil-flooded screw compressor.

- *High reliability and long maintenance interval*—Maintenance interval is typically three to four years. A spare compressor is not required for critical service.

- *Low maintenance cost*—Due to the lube oil system, the rotors and many other parts of the compressor have an oil film on their surface. The life of the rotors is so long that a spare set is not required. The mechanical seal is typically one per casing, so maintenance and replacement cost for the seal is low.

- *Power consumption savings by a built-in slide valve*—The slide valve or unloader adjusts the inlet volume of the compressor, and this equals power savings. By moving the slide valve to the unloaded position the compressed volume of gas by the rotors is reduced, and this reduces the compressor break horsepower. Operational cost is lower with the slide valve in an oil-flooded screw compressor.

- *Single shaft mechanical seal*—The compressor body can be considered as one pressure containing part, so typically only one seal is equipped with one compressor body. As a result, maintenance cost is much lower, and the amount of oil loss is minimal. Also, additional oil is not necessary. This is an advantage for low emission.

- *No compression ratio limitation*—Thanks to the oil acting as a coolant and sealant there is no pressure limitation mechanically. Thermal problems may be considered for other types of compressors; however, oil can be injected into the rotor chamber to absorb the compression heat on oil-flooded screw compressors. A tandem arrangement of two stages may be adopted for better efficiency. Typically a tandem arrangement is used when the pressure ratio is larger than 7.

- *Low noise and high frequency*—Due to the thickness of the compressor casing, noise is low. Since the rotating speed matches a two-pole or four-pole motor speed, noise frequency generated is high compared to that from a reciprocating compressor, so the management of noise is easier.

- *Low vibration and pulsation*—Although the screw compressor is a positive displacement type, the compression mechanism is rotational. It provides a continuously smooth compression and discharge mechanism, so that pulsation from the compressor is negligible. There is no pulsation with an oil-flooded screw compressor, and pulsation bottles are not required, so dampening is not an issue. This can provide simple foundation design.

- *Single skid arrangement*—The compressor and lube oil system are integrated and packaged on a single skid. Thus, transportation and installation are very quick and easy. Interconnecting piping, tubing, and wiring work in the field can be eliminated or kept to a minimum.

- *No cooling water jacket/No gas bypass cooler*—Since oil acts as a coolant in the compression process, the discharge temperature can be controlled by the oil injection flow rate so that the casing structure is made simpler by elimination of the cooling water jacket. The gas bypass cooler can also be eliminated by oil cooling.

Oil-flooded screw compressors are used for various services and are expanding in many applications. Original applications suitable for oil-flooded screw compressors were limited to:

- Low molecular weight applications such as hydrogen or helium gas.

- High pressure ratio applications such as off-gas or flare gas.

- Applications requiring load change such as a fuel gas booster.

After the high pressure oil-flooded screw compressor was introduced to the market, the applications expanded:

- High pressure applications with various services such as a fuel gas booster for a high efficiency-type gas turbine.

- Hydrogen service for a gasoline and diesel desulfurization process.

- Carbon dioxide refrigeration service.

- Gas lift.

## SPECIFIC EXAMPLE OF COMPRESSORS

The following examples show typical oil-flooded screw compressors that are currently used for the gas industries. The purpose of showing these examples is to illustrate modern package designs that are used in the gas industries. All examples have been operating successfully for years after installation.

*Example 1—*
*Fuel Gas Booster for High Efficiency Gas Turbine*

Example 1 (Figure 3) is a motor-driven fuel gas booster, three sets by single-stage, each unit compressing the natural gas 11.0 mmscfd (12,277 $Nm^3/h$), from 170 psig (12.1 bar) to 715 psig (49.3 bar). The power consumption for each unit is 1136 bhp (847 kW); however, it becomes 821 bhp (612 kW) by a slide valve when the suction pressure is changed to 300 psig (20.7 bar). Even the nominal flow rate is the same as 11.0 mmscfd (12,277 $Nm^3/h$).

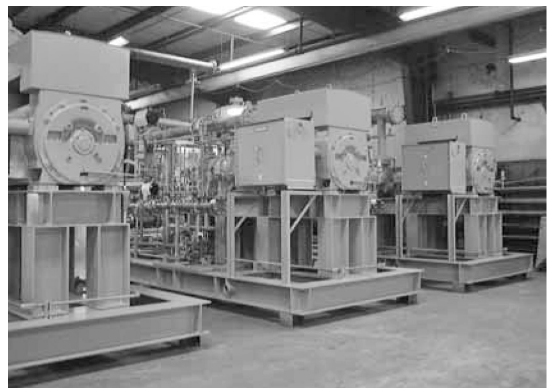

*Figure 3. Motor-Driven Fuel Gas Booster.*

*Example 2—*
*Hydrogen Gas Service*

Example 2 (Figure 4) is a motor-driven hydrogen compressor, one set by one compressor, compressing the pure (99.9 percent) hydrogen gas 6237 scfm (10,024 $Nm^3/h$), from 48 psig (3.31 bar) to 340 psig (23.9 bar). The power consumption for each unit is 1433 bhp (1069 kW). Although the pressure ratio is more than 5.7 and molecular weight is as low as 2.2, a tandem compressor in a one body casing is used.

*Figure 4. Motor-Driven Hydrogen Compressor.*

*Example 3—*
*Combined Refinery Off-Gas and Natural Gas Service as Fuel Gas Booster for High Efficiency Gas Turbine*

Example 3 (Figure 5) is a motor-driven refinery and natural gas compressor separated by two stages. Two gas sources of refinery and natural gas are available in this example. For the refinery gas case, both the first and second stage compressors are utilized and compresses the refinery gas 6900 scfm (11,090 $Nm^3/h$), from 71 psig (4.9 bar) to 675 psig (46.5 bar). For the natural gas case, only the second stage is utilized, and compresses 7500 scfm (12,054 $Nm^3/h$) from 375 psig (25.9 bar). The first stage is also capable of handling natural gas as a backup when the second stage compressor is unavailable. Since the oil screw compressor is a positive displacement type, such flexible applications are possible.

*Figure 5. Motor-Driven Refinery Gas and Natural Gas Compressor.*

## DESIGN ISSUE OF THE HIGH PRESSURE OIL-FLOODED SCREW COMPRESSORS

The high pressure oil-flooded screw compressors are developed by applying a new rotor profile, bearing, etc., and their usage is expanding. Typical operation range for the high pressure oil-flooded screw compressors is shown in Figure 6. The following are key factors for the high pressure oil-flooded screw compressors.

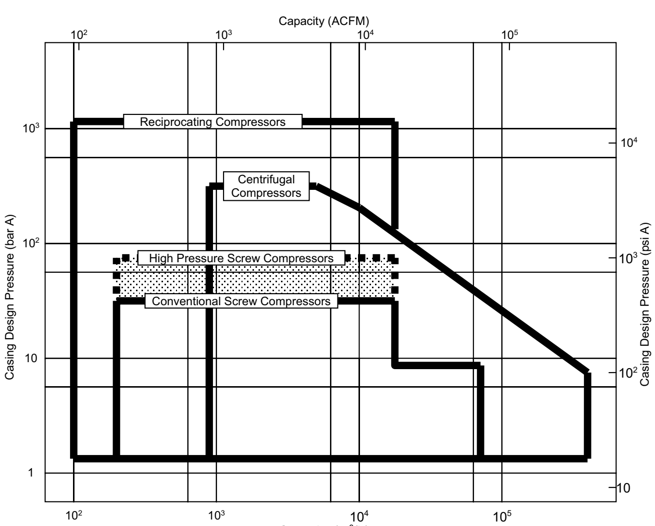


*Figure 6. Typical Operating Range for High Pressure Oil-Flooded Screw Compressor.*

*Optimized Rotor Profile for High Discharge Pressure*

High discharge pressure increases the torque needed to rotate male and female rotors (transmission torque) and the gas load, necessitating higher rotor strength and a larger bearing load capacity. As a solution for these requirements, the number of teeth and the rotor profiles should be optimized.

Studying the bearing load simulation under gas pressure with specific lobe number and rotor length parameters, the optimum lobe numbers to sustain heavy loads can be determined. An optimum design of five teeth for male rotors and seven teeth for female rotors (5 + 7 profile) for example, is shown in Figure 7.

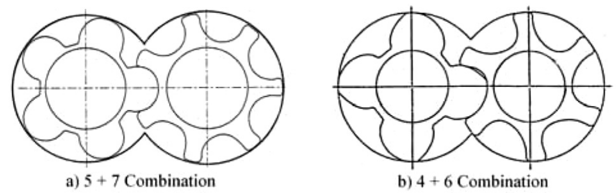


*Figure 7. Rotor Profile.*

A 4 + 6 combination was mainly used in the past as a conventional profile; however, large number combinations will provide a larger shaft diameter, which means journal bearings can be large (refer to detailed discussion in *Bearings*). This also provides not only larger journal bearings, but also the rotor shaft becomes more rigid to avoid excessive deflection in high differential pressure contour on the rotors. Other than the above, the rotor profile should be optimized for high pressure applications.

Though transmission torque is adjustable because of the rotor profile, excessive torque can damage tooth flanks, and insufficient torque can cause unstable female rotor rotation, which increases vibration and noise levels. To solve this problem, a couple of rotor profiles have been designed to produce optimum transmission torque for the rotor material, with the torque shared between the male rotor and female rotor to prevent tooth flank damage and secure rotor actuation even under light load operation. Then, an optimum profile can be finally determined. Another factor is required for the rotor profiles, which is lobe clearance. Less clearance provides less internal leakage, which means high volumetric efficiency can be achieved.

*Bearings*

Journal bearings with sleeve type and thrust bearings with tilting pad type are typically used for the high pressure screw compressor. The rotor lobe tooth combination is again an important factor for the size of the bearings.

As shown in Figure 7 a) and Figure 7 b), a 5 + 7 combination can provide a larger diameter on its shaft than those of a 4 + 6 combination. For example, even if the compressor frame size is the same, it means that a 5 + 7 combination can provide a larger size of journal bearing; a high bearing load can be accommodated with high pressure. These bearings are usually made of white metal, but some other material such as aluminum bearings is used for special applications.

*High Efficiency*

For high pressure ratio application, two-stage compression with a tandem-type compressor may be utilized to achieve significantly higher efficiency characteristics than single-stage. A typical cutaway model is shown in Figure 8. Oil-flooded screw compressors can provide a high pressure ratio with single-stage compression; however, volumetric efficiency is less since internal gas leakage in the compression process increases across the rotor lobes.

This situation will reduce performance in high pressure applications, since differential pressure will also increase in high pressure

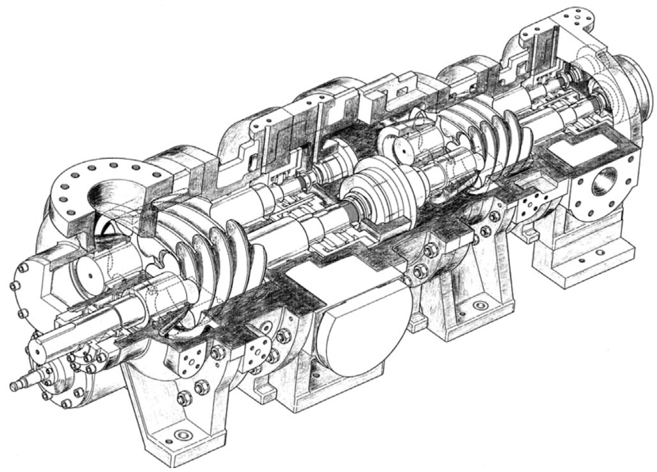

*Figure 8. Tandem-Type Compressor for High Pressure Ratio Application.*

ratio situations. As a resolution, the tandem-type compressor reduces the internal leakage in respective stages to improve volumetric efficiency. Oil is injected as coolant in oil-flooded screw compressors, so the intermediate casing will act as an intercooler to improve the power consumption. Volumetric efficiency and power improvement data for a tandem type compressor is shown in Figure 9.

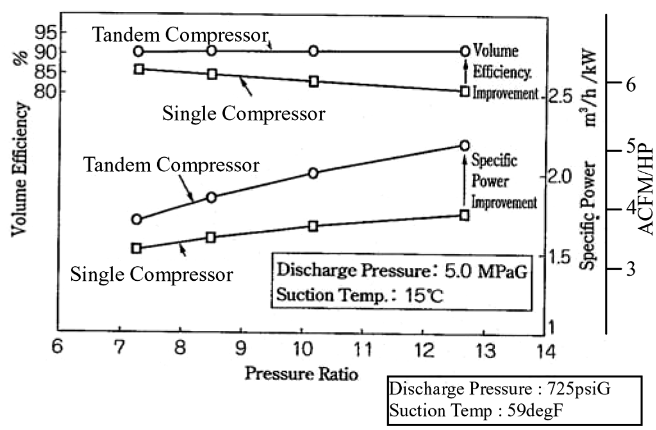


*Figure 9. Performance Comparison Between Single-Type and Tandem-Type Compressor.*

*High Suction Pressure*

A mechanical seal is used for oil-flooded screw compressors, and this seal is one of the important factors to apply high suction pressure on oil-flooded screw compressors. Pressure in the mechanical seal box for the oil-flooded screw compressor is as high as the suction pressure. Therefore, the maximum allowable pressure of the mechanical seal may limit the maximum allowable suction pressure of oil-flooded screw compressors.

The seal should be capable of high differential pressure, since the outside of the seal is typically atmosphere and the inside is equal to the suction pressure. High-strength carbon material is used as a seal ring, and the sliding surface on the ring should be capable of maintaining the seal oil film under high differential pressure conditions. If a backup seal for high pressure applications is requested, tandem arrangement mechanical seals may be used.

*High Pressure/High Pressure Ratio Application*

The tandem type is used for high pressure and high pressure ratios. The tandem-type design consists of a two-stage compressor that can be used as a single-stage compressor, because gas compressed in the first stage is sent to the second stage without discharge. Therefore, the required number of compressors, motors, oil recovery units, and oil separators can be a single unit. Therefore, highly-efficient two-stage compression can be achieved with the same configuration as a one-stage compression unit.

Generally, other compressors with multistage types in order to achieve high pressure and high pressure ratios result in increasing the separate stage. This tandem type, on the other hand, comes in a space-saving, highly-efficient two-stage compressor unit.

*High Pressure/Low Pressure Ratio Application*

Some situations where suction pressure fluctuates widely, such as in the inlet gas pressure swing caused by a mixture of gases at different pressures, require a low pressure ratio such that both the suction pressure and discharge pressure are high. In this case, the slide valve as unloader should be considered. Figure 10 shows the relationship between capacity and power load characteristics when the suction pressure is changed at a constant discharge pressure.

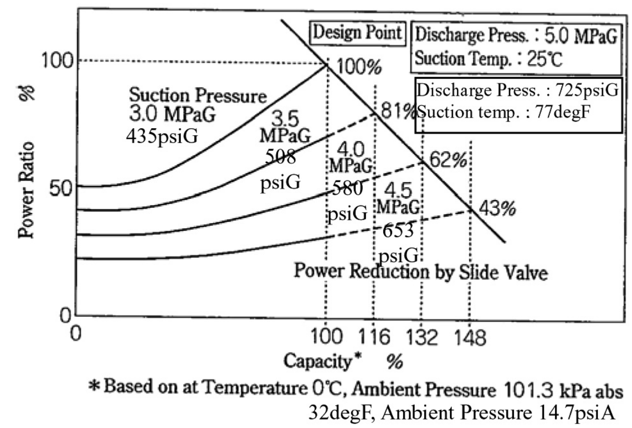


*Figure 10. Performance Change with Slide Valve When Suction Pressure Is Changed.*

For oil-flooded screw compressors in low pressure ratio operation, a suction pressure rise reduces power and increases capacity. Usually, the compressor type is selected on the basis of the lowest suction pressure condition, but in many cases normal operating suction pressure is higher than the design criteria. Consequently, compressors are operated at pressures higher than the design value of full capacity. Slide valve capacity control provides the energy-saving feature under actual operating conditions, and this effect will be larger in high pressure applications.

## PERIPHERAL DESIGN ISSUE

*Oil Separation*

Oil separation is one of the most important factors in the oil-flooded screw compressor application. For example, a severe criterion for oil carryover is required when the oil-flooded screw compressor serves as fuel gas booster for gas turbines. Detailed and accurate oil separation design is required for each application. Typical primary oil separator design is shown in Figures 11 and 12.

As shown in the figures, within the primary oil separator a stainless mesh demister pad is used as the first level of separation and coalescing filters are used as the next level of oil separation. An additional stage of separation using coalescing elements takes place in another vessel called the "coalescing oil separator" or "secondary oil separator." This supplementary stage of separation is usually added under low oil carryover conditions.

Not only does the primary oil separator act as the initial stage of separation, but this vessel also serves as the oil reservoir for the entire system. The bottom volume in the primary oil separator should be considered in order to accommodate a volume of lubrication oil with enough retention time span of approximately two

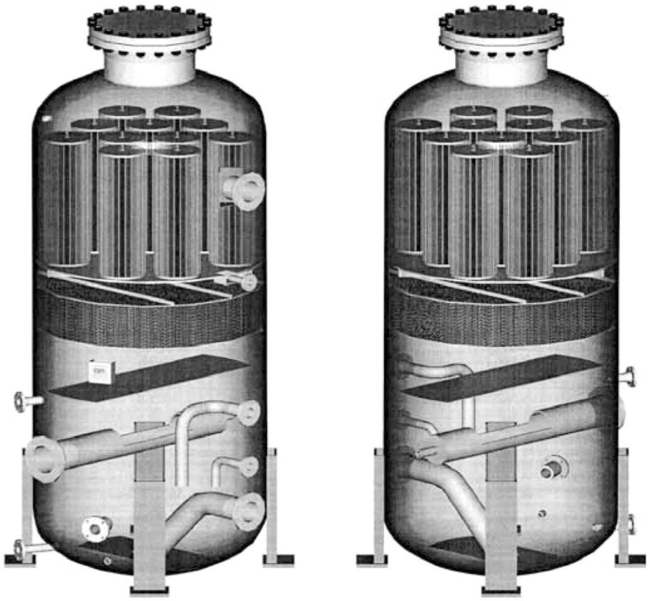

Figure 11. Oil Separator (A).

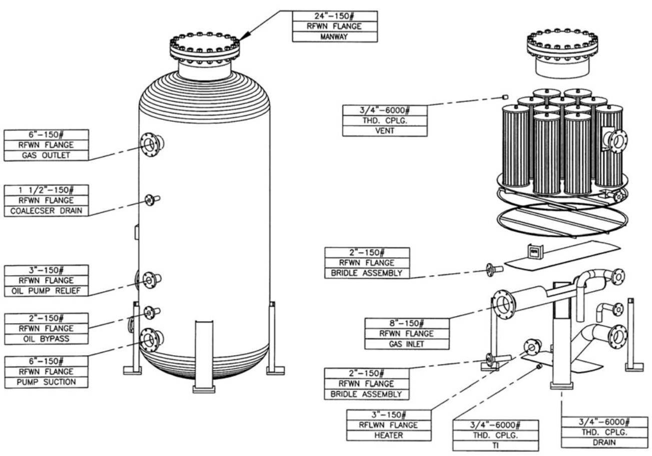


Figure 12. Oil Separator (B).

minutes per API standards. The diameter for the primary oil separator should be determined using velocity of gas, demister pad size requirements, and also the total number of coalescing elements required by volumetric flow.

*Oil Carryover*

Oil carryover is a focal point for end users, and this parameter can be designed by changing the arrangement of the oil separator. Figure 13 shows a typical primary oil separator arrangement with two levels of separation. Stainless steel demisters are the primary level, and single-stage borosilicate coalescing filters as the second level are equipped in one vessel. In this arrangement, expected oil carryover is 1 part per million (ppm) by weight.

Figure 14 shows a common oil separator arrangement with three-stage oil separators. A stainless steel demister is utilized for the primary separator and two stages of borosilicate coalescing filters are being used in the secondary oil separator. In this arrangement, expected oil carryover is 0.1 ppm by weight. In addition to the arrangement shown in Figures 12 and 13, a charcoal absorber can be added downstream of the secondary oil separator. By initiating contact between gas and "activated" charcoal within the absorber, oil carryover requirements of up to 20 ppb by weight can be achieved.

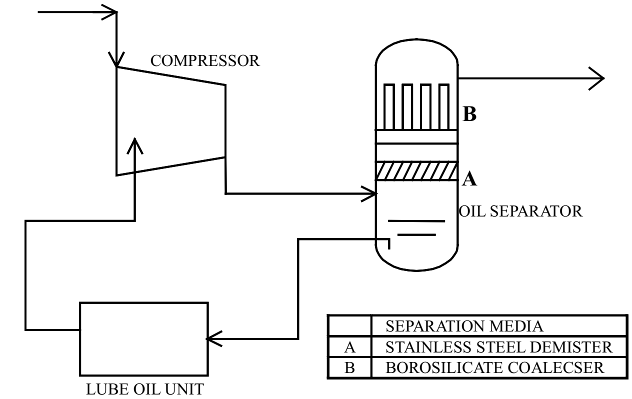


Figure 13. Oil Separation Arrangement—Single Oil Separator.

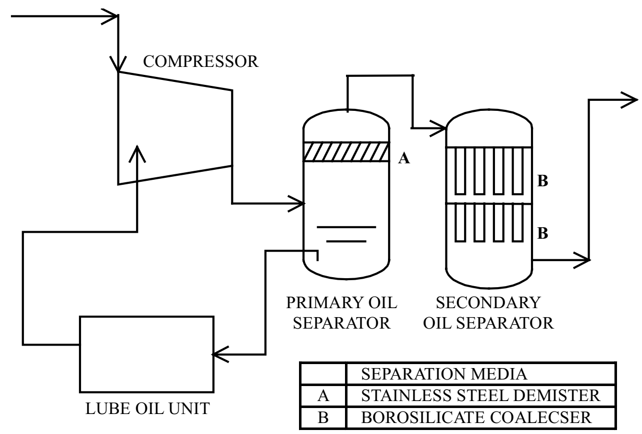


Figure 14. Oil Separation Arrangement—Two-Stage Oil Separator.

*Oil Selection*

The lubrication oil circulation in the system enables the oil to be diluted by process gas. As a result, oil viscosity will be altered over a course of time. The adequate type of oil must be selected in the design phase, considering high pressure conditions inside the system, process gas composition, and water content. Oil viscosity breakdown under the operating conditions should be in an acceptable range for compressor bearings and mechanical seals. Mineral oil is used commonly in most applications; however, other types of oil are used as follows:

- *White oil*—Used for corrosive gas such as vinyl chloride monomer (VCM), food industry gas such as dry ice making.
- *Vacuum pump oil*—Low oil carryover is required, such as the fuel gas booster application.
- *Synthetic oil, polyalphaolefin (PAO) base*—Required when carried oil should not react with process equipment (such as a catalyst) such as a refinery gas application.
- *Synthetic oil, polyalkylene glycol (PAG) base*—Required for heavy hydrocarbon process gas applications, such as refinery or oil and gas gathering applications.

## INSTALLATION, COMMISSIONING, AND STORAGE

*Installation*

In the past, oil-free screw compressors were installed directly onto a mezzanine foundation with single plates. The degree of difficulty of the installation process was very high with that type of arrangement. Presently, for both oil-free and oil-flooded screw compressors, the aforementioned arrangement is becoming very rare. In almost all cases, the use of single/dual pedestal mounting is used even for compressor and motor applications as large as 6000 hp.

Typically, small to middle size oil-flooded screw compressors are packaged on a single skid with a motor, a lube oil system, and a lube oil separation system with process gas piping. Larger size compressors are typically packaged with two skids, one is for the compressor-motor train and the other is for the lube oil unit. The connection points are arranged at the skid edge typically so that difficulty of installation is minimized.

Pulsation issues in the case of reciprocating compressors are not required on screw compressors, which allow foundation design to be done straightforwardly. Also, pulsation studies on piping and the foundation are not required.

### *Commissioning*

In the commissioning period, oil flushing is not generally required if a complete single skid is provided, that system is oil flushed in the manufacturer's scope of production. For the multiskid arrangement, oil flushing is necessary at site; however, even in this case, each skid is typically oil flushed prior to shipment within the manufacturer's scope. The purpose for field flushing in this case is for interconnecting piping.

To complete the commissioning process, an alignment check is performed for all coupled equipment. Also, a complete checklist of items including instruments, valves, and other components must be completed. Once the checklist is complete, the compressor is prepared to operate. After the compressor is started and has operated for approximately 24 hours, an oil analysis is conducted to measure viscosity and verify the overall oil selection.

### *Storage*

At the time of installation and storage, the most important factor is maintenance as it relates to rust prevention. Since oil-flooded screw compressor systems have no connection points to the atmosphere, a nitrogen purge ranging from 5 to 10 psig is the most effective measure to be used. During the storage process only monitoring of the nitrogen pressure will need to be carried out as a minimum.

## OPERATION

After the compressor is put into operation, the standard maintenance practices are to check vibration and perform an oil analysis. The same maintenance scheme is adopted in other types of compressor applications. Oil analysis is conducted every one to six months as a standard.

Differential pressure across the oil separator system(s) should be monitored to determine the condition of the installed coalescing filters over a span of three to six years. If differential pressure exceeds the specified set point given by the filter manufacturer, the filters must be replaced.

The mechanical seal check is done typically after the first one or two years of operation; however, at the time of seal replacement and/or maintenance, a complete overhaul may not be required. Depending on the process application, a major overhaul can take place in the range of three to four years. Common replacement parts of the screw compressor are the mechanical seal and bearing components. There is only one seal per compressor housing; therefore, the overall cost of maintenance is minimized.

A huge advantage during operation of the oil-flooded screw compressor is reduction of power consumption in the unloaded condition. In conjunction with the turndown ratio advantage, the compressor slide valve can accommodate a significant swing in suction pressure.

## CONCLUSION

As a result of inexpensive operation, low maintenance cost, and high reliability of oil-flooded screw compressors, the overall demand is increasing rapidly. The high pressure oil-flooded screw compressors are continually being introduced with new technologies and enhancements. From new rotor profiles and expansion of its applicable range, oil-flooded screw compressors (also oil-free screw compressors) will become the leading method of gas compression applications.

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