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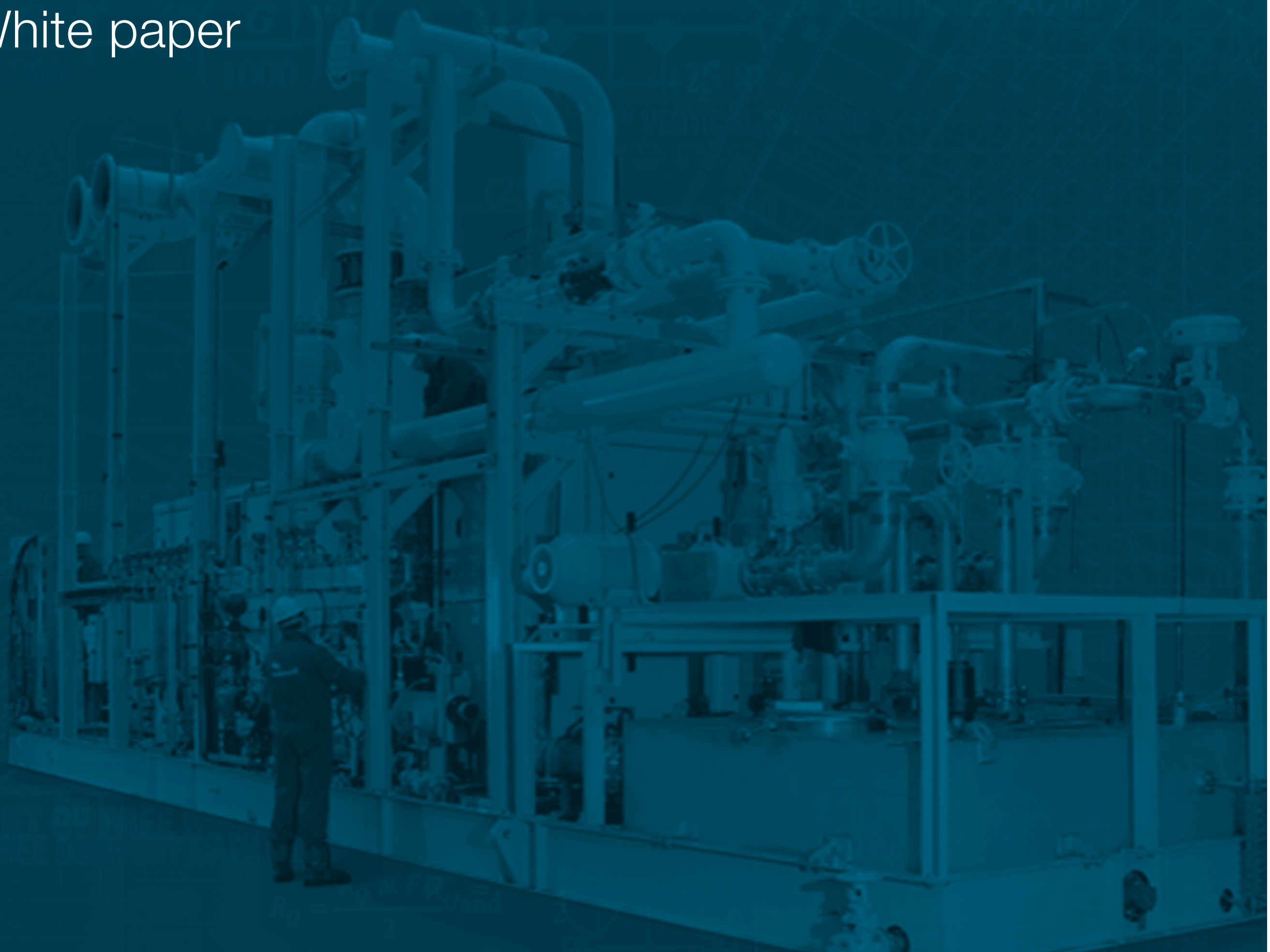
Oil-free twin screw compressor clearance management

White paper



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Abstract

Oil-free twin screw compressors are often required over their oil-injected counterparts to allow the handling of a range of different gases, however managing the operational clearances within can be challenging.

Oil-free compressors operate at much higher temperatures than oil-injected compressors, with zero contact between the rotors and no cooling oil in the rotor chamber to seal the clearance gaps.

They must be designed using advanced clearance management techniques in order to maximise their efficiency whilst maintaining the exceptional reliability expected of a Howden compressor.

This paper describes the theory behind oil-free compressor operations, clearances and conventional methods of clearance management. It details the improved clearance management methods that have been developed and integrated into Howden's current oil-free screw compressor range. Furthermore, this paper will explain the key benefits that customers will gain from these methods.

Background

When handing hazardous or corrosive gases, gases with high levels of liquid, dirt or particulates, or when contamination of the gas being processed is an issue, the use of oil-free twin screw compressors is often the best approach.

Howden's oil-free twin screw compressor range is involved in a wide range of industries and processes, such as:

- Chemical
- Foundry
- Mining
- Oil & Gas
- Petrochemical
- Power Generation
- Refinery

Appendix 1 provides more detailed information on the fields of application where oil-free compressors are used. In these industries, Howden are experienced in compressing a high diversity of different gases of varying molecular weights, including polymer forming and unpredictable gases. **Appendix 2** lists multiple project references where oil-free compressors have been installed.

Oil-injected twin screw compressors operate with oil injection into the rotor chamber, which is used for cooling, sealing of the clearance gaps and lubrication of the rotors – in which, the directly driven male rotor drives the female rotor using the injected oil as a hydrodynamic film to maintain efficiency and prevent wear.

Oil-free screw twin compressors are designed to operate using a timing gear setup to synchronise the rotors and therefore negate the need for oil injection. Although this allows the handling of gases possible in an oil-injected compressor, it adds a more complex challenge in the clearance management process during the design stage.

This is due to the higher temperatures experienced within the compressor and the lack of clearance gap sealing via injected oil. **Figure 1** shows a dissected view of a Howden oil-free screw compressor.

This paper will demonstrate that, although complex, the management of these critical clearances has been achieved in the Howden oil-free screw compressor range. This has been realised through extensive research and development, and has been successfully applied into the current screw compressor range.

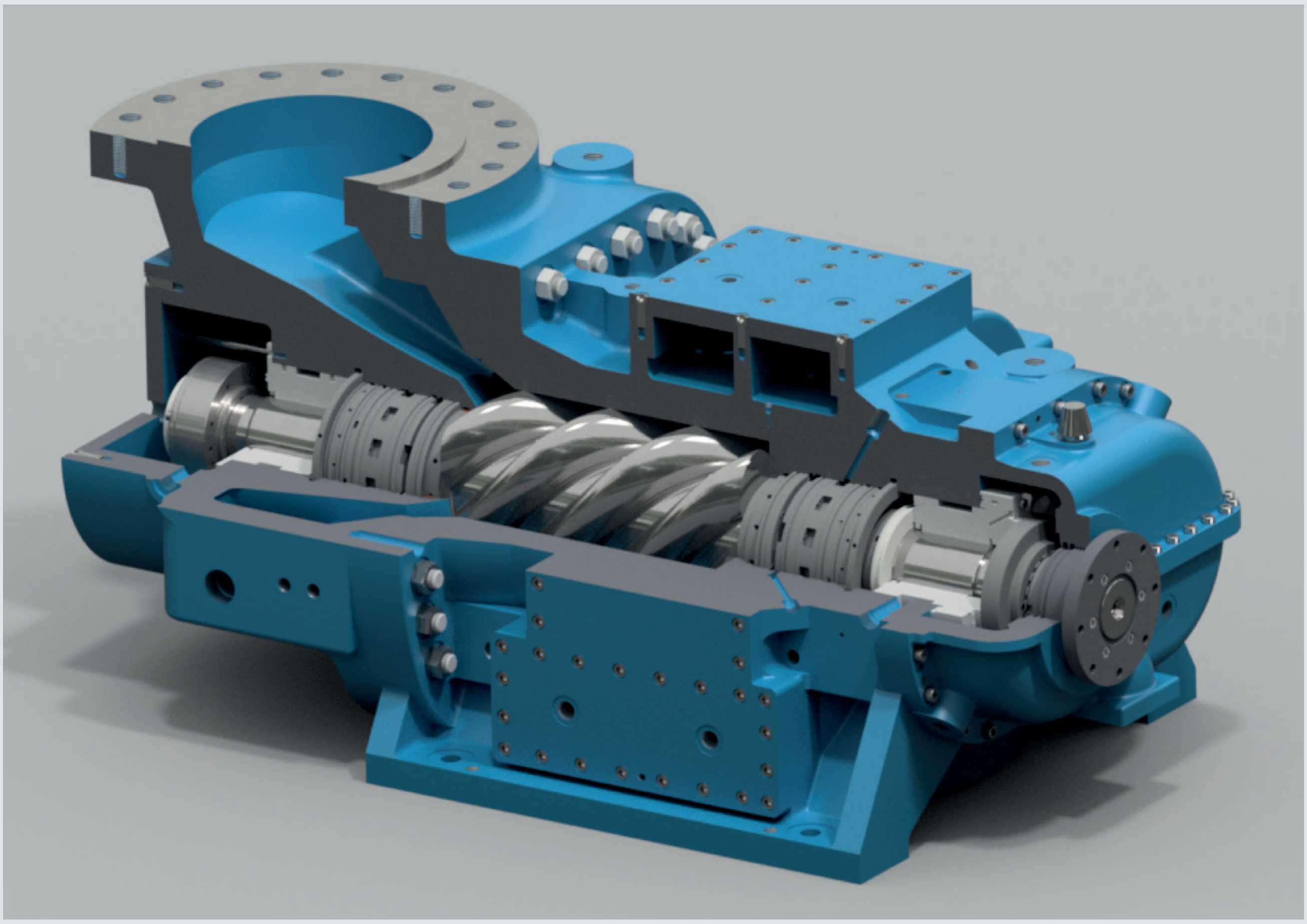

Figure 1: Howden oil-free screw compressor.

Twin screw compressor operation

Twin screw compressors are positive displacement rotary compressors, in which the compression of gas is achieved by the intermeshing of two helical rotors with a closely fitting casing.

Figure 2 is an illustration of the rotors in mesh at the main stages of the compression cycle.

At the beginning of the compression cycle, the gas is drawn in through the inlet port to fill the cavities between adjacent lobes on the male (right) and female (left) rotors. As the rotors turn, these cavities become chambers which trap the gas between the rotors and casing.

This begins to move axially from the suction to the discharge end. The volume of each chamber decreases gradually along this path due to the helical form of the rotors. This decrease in volume continues until the chamber and becomes a cavity which is exposed to the outlet port, where the compression cycle is completed and the process of discharging the compressed gas begins.

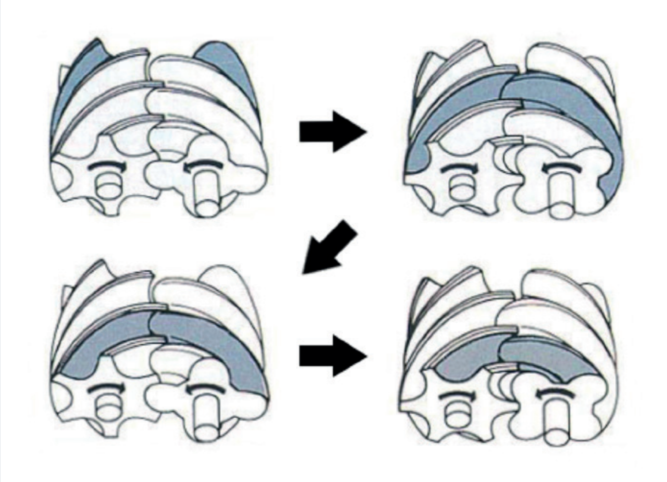

Figure 2: Twin screw compressor operation.

Leakage paths

The main clearance gaps in a twin screw compressor that create a path through which leakage can occur are: the rotor to casing 'axial' gap, the rotor to casing 'radial' gap and the rotor to rotor 'interlobe' gap.

Figure 3 displays these main leakage paths on a simplified screw compressor sectional view.

Axial

The main axial leakage path is the clearance gap between discharge end face of the rotor and the discharge end wall of the casing. The presence of this gap enables the gas to leak across the rotor end face from one cavity to the following, and in some cases directly to suction pressure.

Radial

The main radial leakage path is the clearance gap between the rotor tips and the casing bores. The presence of this gap enables the gas to leak across the male and female rotor tip seals from one cavity to the following.

Interlobe

The main interlobe leakage path is the clearance gap between the male and female rotors. The presence of this gap enables the gas to leak across the rotor flanks from one chamber to the following.

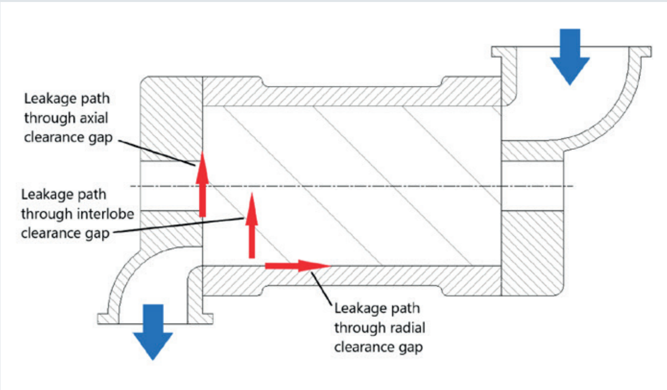

Figure 3: Oil-free compressor main leakage paths.

Influencing factors

During compressor manufacture, assembly and operation there are a number of factors which can affect the main clearance gaps either detrimentally or beneficially.

The main influencing factors are: manufacture and assembly tolerances, bearing clearances, thermal distortion, pressure distortion and rotordynamics.

Manufacture and assembly tolerances

Although the process for managing the compressor clearances begin in the design phase, it is arguable that the most critical stage is during the manufacture and assembly.

If critical components such as the rotors and casing are manufactured or assembled out of tolerance, then the performance and reliability of the compressor are compromised from the start. **Figure 4** shows an image of a pair of machined oil-free screw compressor rotors undergoing a pre-assembly clearance check.

The rotor machining features will impact the three main clearances and therefore must be carefully kept within tolerance are: the rotor profile, rotor body length and the shaft journal diameter and position. On the casing, the tolerances of the rotor and bearing bore diameters, lengths and positions must also be tightly controlled in order to adhere to the design clearances.

Assembly of the manufactured components must be carried out using the appropriate processes and methods, to ensure that each is positioned and fixed in place correctly. It should also be noted that the critical task of setting the axial clearance gap between the discharge end face of the rotor and the discharge end wall of the casing, is performed during the assembly process. **Figure 5** shows an image of a Howden oil-free screw compressor during the assembly process in the Renfrew facility.

The environment in which machining and assembly takes place is also a factor, primarily the ambient temperature as this will influence the level of thermal distortion experienced during operation of the finished compressor. For this reason, Howden machine and assemble their compressors in a controlled environment, to ensure that the finished product stays as true to the design as possible.

Figure 4: Oil-free compressor rotor clearance check.

Figure 5: Oil-free compressor assembly.

Influencing factors

Bearing clearance

In addition to transferring the loads present during compressor operation, the axial and radial bearings, or more specifically the clearances present within them, also have an effect on the three main clearance gaps.

Figure 6 shows one of the combined axial and radial bearings available in a Howden oil-free compressor.

The axial bearing clearance plays an important part in the design of the axial clearance gap, whilst the radial bearing clearance will impact both the radial and interlobe clearance gaps.

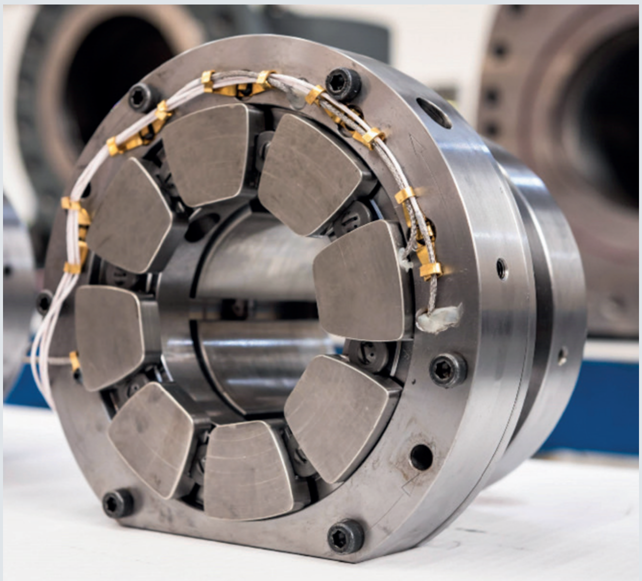

Figure 6: Combined axial and radial bearing.

Thermal distortion

Oil-free twin screw compressors tend to operate at elevated discharge temperatures compared to their oil-injected counterparts, and therefore their rotors and casing will be susceptible to greater levels of thermal distortion.

Thermal expansion of the rotors causes the radial and interlobe clearance gaps to decrease, as the rotor lobes expand radially outwards into the casing and opposing rotor.

Conversely, thermal expansion of the casings can cause the radial and interlobe clearance gaps to increase or decrease, due to the complex nature of thermal distortion in these components.

Figure 7 shows an example of the overall displacement in the assembled main and inlet casings of an oil-free screw compressor due to thermal distortion.

The effects of thermal expansion in both components are not constant either, as both are made of different materials and therefore do not expand at the same rate. During operation, the discharge end is at a higher temperature than that of the suction end which causes a higher degree of thermal expansion in this region and consequently distorting the rotors and casing.

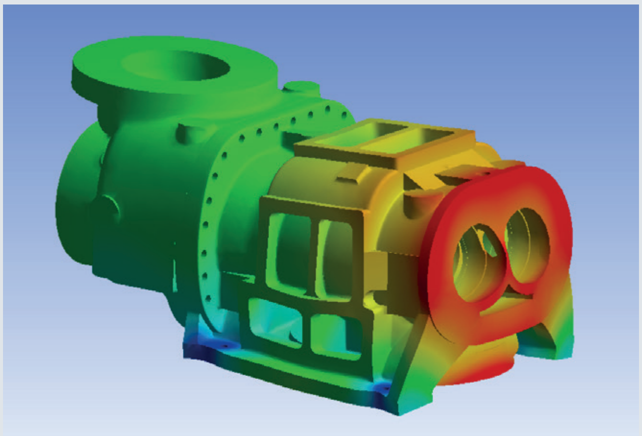

Figure 7: Casing displacement due to thermal distortion.

Influencing factors

Pressure distortion

A key feature of Howden oil-free screw compressors is that they are able to operate at higher pressures than traditional oil-free screw compressors, but with this comes a greater magnitude of pressure distortion.

The pressure causes the rotors to bend in the form of static deflection, with varying levels of deflection on the male and female rotors

This is due to the different profile shape on each. Due to the bending, the deflection of each rotor also varies axially, and the direction of deflection depends on the layout of the compressors suction and discharge ports.

The radial and interlobe clearance gaps are impacted by these deflections, so they must be carefully considered.

The casing is also subjected to the pressure loads inside the compressor and the loadings imposed by the suction and discharge ports, but these are relatively small and often ignored in a clearance analysis.

Rotordynamics

When designing the compressor rotors, specific attention is paid to ensure that they are as rotordynamically stable as possible.

However, the imbalance in the rotors shafts, due to design features and manufacturing imperfections, results in dynamic deflection due to 'whirling' of the shafts during operation.

The male and female rotors whirl with differing intensities of deflection due to the different profile of each. As with the static deflection, the magnitude of dynamic deflection of each rotor also varies axially, affecting the radial and interlobe clearance gaps by different magnitudes along the length of the rotors. **Figure 8** shows an example of a rotor whirl mode shape, generated using Howden's proprietary rotordynamics simulation software.

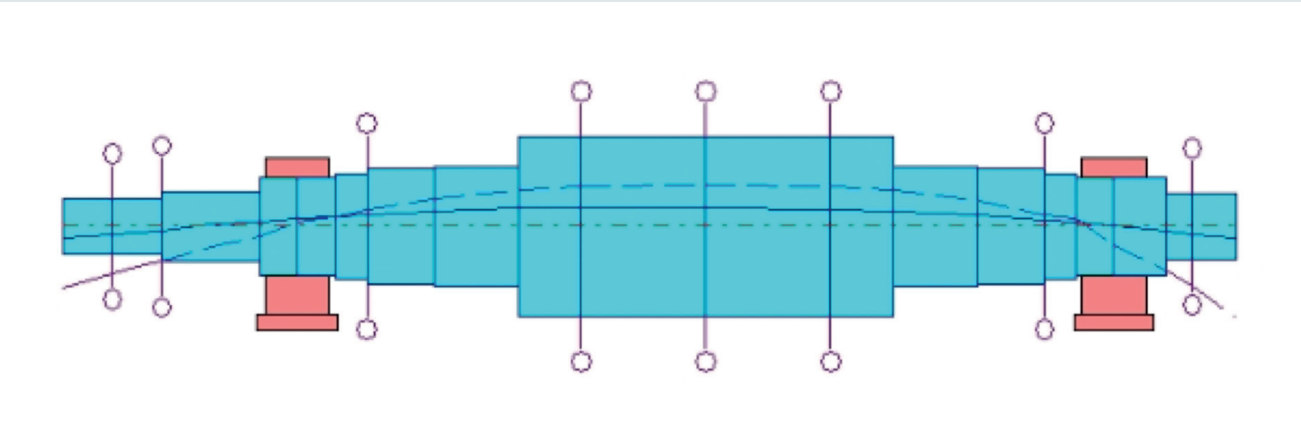

Figure 8: Rotor whirl.

Impact of clearances

No matter how technically advanced the compressor design is, if the clearances are not designed and implemented correctly then the achievable performance will always be compromised.

The main compressor performance factors impacted by the clearances are:
Efficiency
Reliability
Achievable operating conditions

Efficiency

Generally speaking, a compressor with tighter clearances at the three main gaps will be more efficient, as the leakage paths will be smaller and therefore less leakage of the gas being compressed will occur. **Figure 9** shows a chart highlighting the theoretical effect of increasing the three main clearance gaps on the volumetric efficiency of the compressor, with the data generated using SCORG compressor design software.

It is not as simple as purely designing the rotors and casing to have minimal clearances though, as the effects of the previously discussed influencing factors must also be taken into account, and accommodation made for each within the final clearances.

For example, thermal expansion of the rotors and casing are dependent on the operating conditions of the manufactured compressor, specifically the discharge temperature. In order to maximise efficiency as these conditions, the clearances must be designed so that they are as small as possible for the given temperature, without compromising the reliability of the compressor.

Reliability

Although tighter clearances are one of the key factors for a more efficient compressor, the clearances must not be so tight that contact occurs during normal operation.

Oil-free compressors are designed to eliminate any interlobe contact during normal operation. This is done through a sophisticated timing gear setup - so any contact due to incorrect clearance management would lead to an increase in component wear, and in turn, if the contact is excessive then it will result in failure.

Excessive axial or radial contact is also a major issue which can lead to damage or failure, further highlighting the importance of the clearance management process.

It should be noted that slight contacts due to momentary upsets in the compressor operating conditions are acceptable, and the fact that these slight contacts are not detrimental to the operation and life of the compressor is actually an advantage of this type of compressor.

Achievable operating conditions

A sub-optimal clearance design can also limit the operating conditions achieved by an otherwise capable compressor. If the compressor design and materials are able to withstand elevated discharge temperatures, pressures and speeds, with the only limiting factor being the clearances at these conditions, then this limits the commercial opportunities of the compressor, resulting in a major issue.

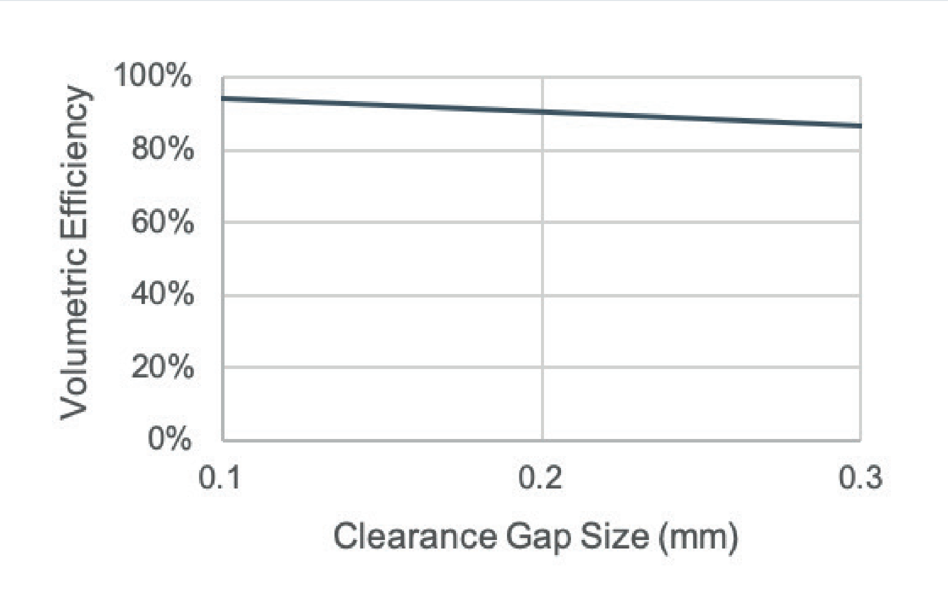

Figure 9: Volumetric efficiency vs.clearance gaps.

Conventional clearance management methods

Conventionally, a number of methods have been employed to attempt to manage the clearances in oil-free screw compressors, some more effective than others. Unfortunately, the majority of these methods introduce new problems, which must then be managed in parallel.

The key conventional clearance management methods previously introduced are:
Rotor tapering
Rotor cooling
Introduction of a basic cooling jacket

Rotor tapering

In an effort to combat mainly interlobe, but to a lesser degree radial, a taper can be introduced on the male rotor. This is done through contact at operating conditions, consisting of elevated discharge temperatures. This means that the outer diameter of the rotor is machined to gradually decrease towards the discharge end to a predetermined value, and depending on the discharge temperature required of the compressor either a 'single' or 'double' taper can be applied. **Figure 10** shows simplified examples of a non-tapered (parallel) rotor, a rotor with a single taper and a rotor with a double taper.

The downside of this method is that machining of the tapered rotor is a time consuming and complicated process and introduces room for errors which could cause the entire rotor to be scrapped. Another disadvantage is that although the process solves the issues of interlobe and radial clearances of the male rotor, the taper is not applied to the female rotor and therefore radial contact with the casing is still possible at higher temperatures.

Rotor cooling

Rotor cooling seeks to manage the compressor radial and interlobe clearances by lowering the temperature of both the male and female rotors, and therefore limiting the amount of thermal expansion imposed on them. Cooled rotors have an internal cavity through which cooling oil is pumped from the discharge to inlet ends, removing heat from the rotor bodies. **Figure 11** shows simplified examples of a solid, non-cooled rotor and a hollow, cooled rotor.

Similar to tapered rotors, the manufacture of cooled rotors is a complex and time consuming process which introduces room for costly errors. To add to this, as the cooled rotors are essentially hollow, the strength of each rotor is comprised which leaves it more susceptible to pressure distortion and rotordynamics issues.

The hollow rotor also reduces the sectional area and therefore the thermal flux away from the hot areas of the rotor is reduced, decreasing thermal stability.

Basic cooling jacket

The aim of implementing a cooling jacket around the compressor casing is to limit thermal distortion imposed upon it and therefore manage the internal clearances. The cooling jacket consists of an enclosed chamber around the rotor casing, through which a cooling medium, usually water or oil, is pumped to remove heat from the casing.

The utilisation of the cooling jacket is a proven concept for clearance management, which has plenty of scope to be further developed in order to optimise its performance.

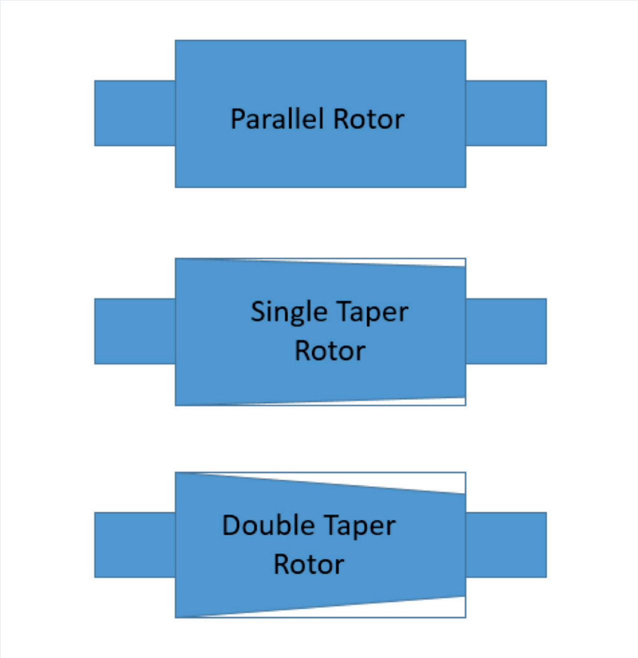

Figure 10: Rotor tapering.

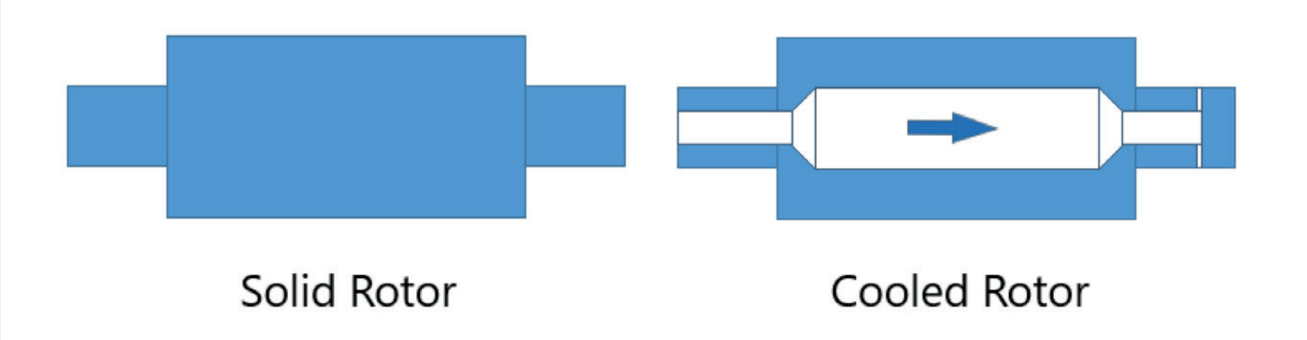

Figure 11: Rotor cooling.

Howden's improved clearance management methods

In order to tackle the issues associated with conventional clearance management methods, Howden have developed an improved set of methods which have now been implemented into our oil-free screw compressor range. These new methods have been designed to effectively manage the clearances without the addition of any unintended side effects.

The key improved clearance management methods developed are:
Rotor temperature cuts
An optimised cooling jacket
The process of analysis based clearance management

Rotor temperature cuts

Rotor temperature cuts are an evolution of the combination of the conventional rotor tapering and cooling methods, designed to solve the issues of interlobe and radial contact at elevated discharge temperatures without the inherent problems associated with these methods.

There are a range of standard temperature cuts available (110˚C, 180˚C and 225˚C in the HXP range and 110˚C and 150˚C in the HXC range) which will limit the discharge temperature to that of the cut chosen, with both rotor outer diameters and interlobe clearances of each cut optimised to give maximum performance, reliability and zero contact at this temperature. Figure 12 shows simplified examples the different temperature cuts available as standard on the HXP and HXC oil-free compressor ranges.

Solid, parallel rotors are used for this method, meaning that the manufacturing, structural and thermal issues associated with rotor tapering and cooling are no longer prevalent.

Optimised cooling jacket

The optimised cooling jacket takes the conventional cooling jacket and extends it to cover more of the high temperature discharge area, which has been moved to the bottom of the compressor due to the newly adopted 'top-in bottom-out' configuration, further limiting thermal distortion of the casing in this area and as a result optimising the internal clearances. The path of the enclosed chamber through which the cooling medium is pumped has also been improved in order to remove heat from the casing as efficiently as possible.

The hollow rotor also reduces the sectional area and therefore the thermal flux away from the hot areas of the rotor is reduced, decreasing thermal stability.

Detailed clearance analysis

The final improved clearance management method implemented into Howden's oil-free screw compressor range is a detailed clearance analysis of each individual compressor produced, which takes into account the compressor operating and the ambient conditions of the location where the compressor is to be installed.

The analysis performed combines a complete tolerance stack-up calculation with thermal distortion, pressure distortion and rotordynamics simulations in order to predict the axial, radial and interlobe clearances whilst the compressor is operating at its intended duty. This analysis will flag up any potential issues before the manufacture of the compressor has begun, and gives a further level of confidence that the performance and reliability of the compressor will be optimal.

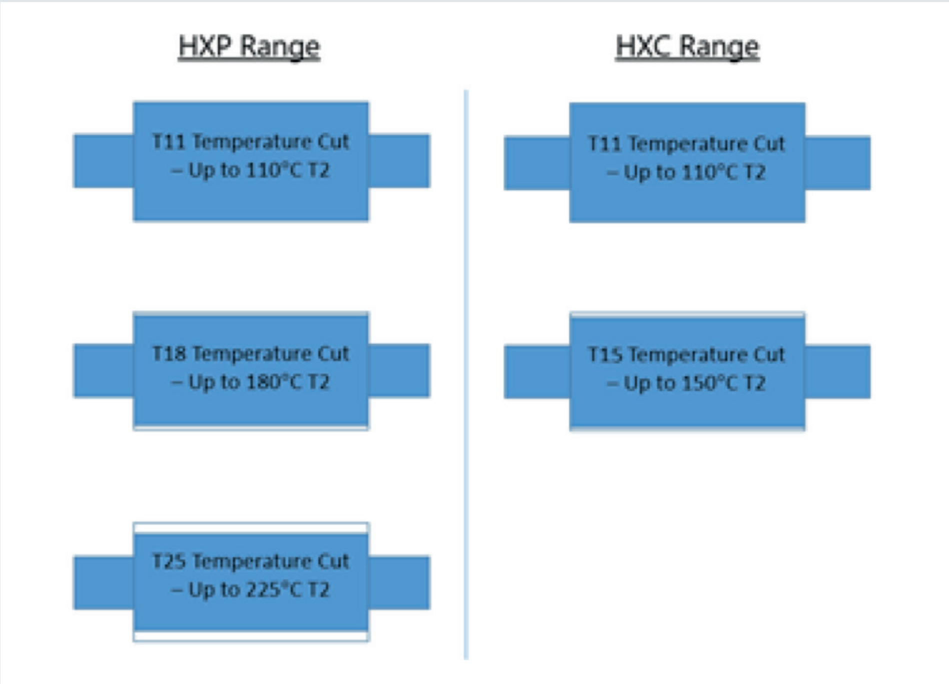

Figure 12: Rotor temperature cuts.

Customer benefits

Ultimately, the improvements in clearance management were developed and implemented by Howden in order to benefit the customer and improve their experience with the Howden product. **The most significant customer benefits are:**

An increase in efficiency

Improved reliability

The ability to handle more challenging operating conditions

Increased Efficiency

With the temperature cut of each set of rotors closely matched to the intended discharge temperature of the compressor, it is ensured that the radial and interlobe clearances are at the optimal value to minimise the leakage paths and therefore provide peak efficiency. This means that it will take less power to compress a specified volume of gas, reducing the running costs of the compressor

Improved Reliability

Another benefit of the individually matched rotor temperature cuts is the probability of radial and interlobe contact during normal operation has been greatly reduced. This will ensure that the chance of an expensive failure is minimised, reducing the amount of servicing needed on the compressor, and in turn reducing its overall running costs.

Challenging Conditions

A number of different factors introduced by Howden's improved clearance management methods allow more challenging operating conditions to be met with ease by the oil-free screw compressor range.

The combination of the rotor temperature cuts, an optimised cooling jacket and detailed clearance analysis means that the discharge temperature of the oil-free screw compressor range has been able to be raised confidently to 225˚C in the HXP range and 150˚C in the HXC range.

These elevated discharge temperatures will allow higher pressure ratios to be achieved. This feature has an added benefit, as duties which previously required a two stage setup consisting of two compressors, may possibly be achieved using a single compressor.

Also, with cooled, hollow, rotors are no longer necessary for clearance management at these temperatures. The increase in rotor strength will permit greater pressures to be handled and further increase the compressors ability to deal with higher differential pressures.

Conclusions

This paper highlights the importance of effective clearance management methods and the key factors which must be considered in the design phase. It also explains the steps Howden have taken to optimise existing methods, as well as develop new and improved clearance management processes in the full oil-free compressor range. **The main points to take away are:**

Maximised performance and reliability

The use of rotor temperature cuts combined with the optimised cooling jacket present in Howden's oil-free screw compressor range allows the radial and interlobe clearances to be optimised for the specific operating conditions of each individual compressor, maximising performance and reliability.

Peace of mind

The detailed clearance analysis carried out on each oil-free screw compressor ensures that any potential issues can be dealt with before they arise, giving an extra level of confidence that the compressor will perform optimally when operational on-site.

Optimum performance for challenging conditions

The improved clearance management methods introduced by Howden will benefit the customer with increased efficiency, improved reliability and the ability to handle more challenging operating conditions.

Appendix 1

Fields of application

There are many applications benefitting from the use of oil free screw compressors. These often occur in situations involving polymer forming gases, gases with varying composition or operating conditions, process gases with liquid carry over or dirty and corrosive gases.

Oil and gas production

Flash gas/low pressure gas boosting within onshore and offshore separation plants.

Off/vent gas processing from stabilization units.

Tail gas processing within gas treatment plants.

Flare gas recovery within onshore and offshore production facilities.

Petrochemical and chemicals

Off/vent gas processing in a wide range of plants dealing with highly corrosive and difficult gases (e.g. polyethylene, acrylonitrile, styrene, vinyl chloride monomer, maleic anhydride, soda ash).

Feed and recycle gas boosting of butadiene, acetylene and hydrogen (within multiple plants such as linear alkyl butadiene or aniline).

Oil refining

Off/vent gas processing within production units such as Fluid Catalytic Converters, Delayed Cokers, CDU and Alkylation.

Flare gas recovery systems.

Tail gas processing within hydrogen recovery plants.

Metal production

PTS (nitrogen) compression for conveying of pellets in certain Direct Reduced Iron processes.

Coke oven gas compression.

Industrial utilities

Fuel gas boosting for gas turbine power units within energy production facilities.

Appendix 2

Selected references

Flare gas compression
2 stage system in offshore oil development (Abu Dhabi)
Volume: 2867 m^3/h (1687 cfm)
Pressure: 1 bar to 6.8 bar a
(14.5 to 98.6 psi)

LP booster
2 stage system in offshore oil development (Canada)
Volume: 5502 m^3/h (3238 cfm)
Pressure: 1.4 bar to 10 bar a
(20.3 to 145 psi)

Nitrogen regeneration
Propylene plant (Abu Dhabi)
Volume: 4360 m^3/h (2566 cfm)
Pressure: 3 bar to 6 bar a
(43.5 to 87 psi)

Fuel gas booster
Multiple units for offshore oil platform (China)
Volume: 3958 m^3/h (2329 cfm)
Pressure: 4.4 bar to 9.6 bar a
(63.8 to 139.2 psi)

Hydrogen regeneration
Oil refinery (Belarus)
Volume: 5491 m^3/h (3231 cfm)
Pressure: 5.8 bar to 8.4 bar a
(84.1 to 121.8 psi)

Deheptanizer net gas
Petrochemical plant (South Korea)
Volume: 15150 m^3/h (8916 cfm)
Pressure: 1 bar to 7.0 bar a
(14.5 to 101.5 psi)

Stabilizer off gas
Oil production facility (Iraq)
Volume: 11995 m^3/h (7059 cfm)
Pressure: 1.1 bar to 3 bar a
(15.9 to 43.5 psi)

Vapor recovery
Oil field development (Malaysia)
Volume: 1748 m^3/h (1028 cfm)
Pressure: 4.4 bar to 12.9 bar a
(63.8 to 187 psi)

VCM recovery
2 stage system in petrochemical plant (Mexico)
Volume: 5010 m^3/h (2948 cfm)
Pressure: 1.1 bar to 5.0 bar a
(15.9 to 72.5 psi)

Butadiene recycle
Refining and petrochemical complex (India)
Volume: 15371 m^3/h (9047 cfm)
Pressure: 1.6 bar to 5.5 bar a
(23.2 to 79.7 psi)

PTS gas compression
Steel plant (Egypt)
Volume: 10457 m^3/h (6154 cfm)
Pressure: 2.9 bar to 11.3 bar a
(42 to 163.8 psi)

PSA nitrogen startup
Oil refinery (Peru)
Volume: 1536 m^3/h (904 cfm)
Pressure: 8.8 bar to 10.8 bar a
(127.6 to 156.6 psi)

Butane BOG recovery
NGL plant (UK)
Volume: 3900 m^3/h (2295 cfm)
Pressure: 0.9 bar to 3.1 bar a
(13 to 44.9 psi)

Flash gas compression
Offshore oil platform (Dubai)
Volume: 5447 m^3/h (3205 cfm)
Pressure: 2.3 bar to 11.4 bar a
(33.3 to 165.3 psi)

VDU Off Gas
2 stage systems for oil refinery (Saudi Arabia)
Volume: 806 m^3/h (474 cfm)
Pressure: 1.2 bar to 3.5 bar a
(17.4 to 50.7 psi)

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