OPTIMIZE RECIPROCATING COMPRESSOR EMISSIONS MANAGEMENT

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EDITOR'S NOTE

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ABSTRACT

The nation's natural gas infrastructure is dependent upon more than 60,000 reciprocating compressors for gathering, processing, transportation, and storage. These machines are critical to the entire supply chain but they have been identified as a major source of fugitive methane emissions.[1,2] These fugitive emissions not only negatively impact the environment but can also pose a significant safety risk to operators on and around the compressor deck.

The fugitive emissions primarily stem from the piston rod sealing systems.[2] The piston rod sealing systems utilize a pressure packing as the primary seal, but pressure packings are not perfect seals. To control this leakage, the piston rod sealing system is also dependent upon the distance piece, vent lines, drain lines, secondary seals, and buffer seal arrangements.

This article discusses dynamic packing case models, evaluates internal pressure distributions, breaks down how the case geometries impact vent cup pressures and the cup-to-cup leakage rates, and the overall performance of the case. The evaluation links the packing models to the entire emissions management system with a discussion on the ideal configurations. The article will conclude with an implementation roadmap to select the optimal emissions management system based on compressor configuration and what is available at the given site.

PRESSURE PACKING INTRODUCTION

The purpose of the pressure packing is to keep the high-pressure gas in the crank end (CE) compression chamber. The pressure packing case accomplishes this using a series of sealing rings and cups with an example of a common case illustrated in Table 1 and Figure 1. The first cup is the nose cup, which seals against the CE head with a gasket, and can either have a breaker ring or a single-acting (SA) sealing ring set. The second cup is a seal cup with the addition of a lubrication delivery port. The third and fourth seal cups also have SA seals. The SA rings seal in one direction (left to right in the Figure 1 example), but allow the hot gas to escape back in the chamber during the reexpansion stroke (right to left). The fifth cup is the vent and purge cup. This is the final seal in the packing case, with the goal to route all seal ring leakage to the vent line. Finally, there is the flange used to bolt the packing case to the CE head with the required connections.

Note there are several different ring styles and packing case configurations. The example in Table 1 captures the most common in use.

RADIAL, TANGENT, BACK-UP SEALING SETS

There are several different types of sealing ring sets available for packing cases, but the most common is the radial, tangent, back-up (RTB). Some ring sets may seal better than others, but regardless of design or quantity, every ring set will typically leak measurable amounts. Causes for leakage vary but can include the following: geometry imperfections from manufacturing, dimensional changes with temperature, geometric changes due to wear, deformation/creep under load, or debris trapped between surfaces.

Leakage paths in a ring extend well be-

Number	Description
1	Nose Cup + Seal
2	Seal + Lube Cup
3	Seal Cup
4	Seal Cup
5	Vent + Purge Cup
6	Flange

Table 1. Packing Case Component Description

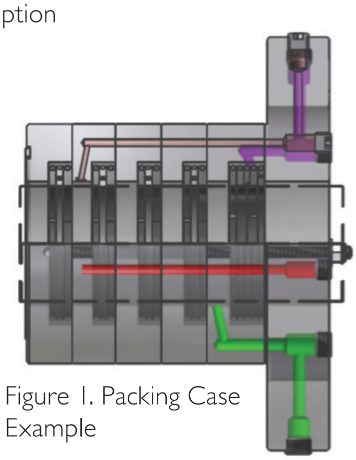

Figure 1. Packing Case Example

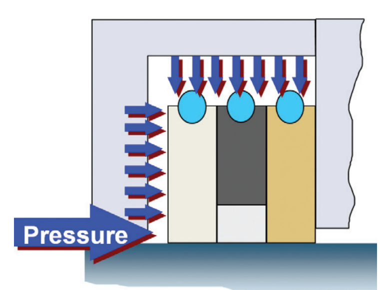

Figure 2. In-Cup Pressure Distribution

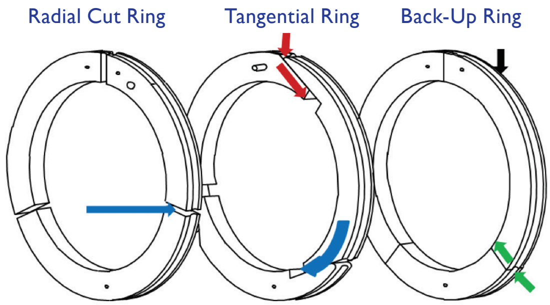

Figure 3. RTB Leakage Paths. Blue line – in through the radial ring end gap and circumferentially through the surface disparities and bore edges of the radial and tangent rings; red line – through the surface disparities and tangent cut edges on the tangent ring; green line – through the surface disparities and edges of radial joints on the back-up ring; black line – through the surface disparities between the rings and between the ring and the cup face; not shown – between the rings and the rod – rings not gripping the rod, surface disparities, rings at wear stops.

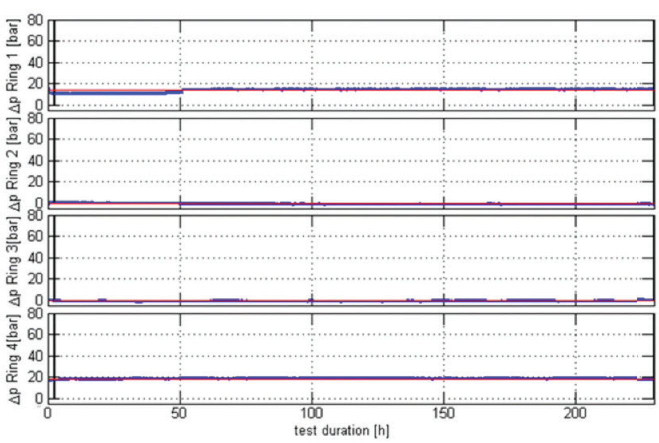

Figure 4. In-Case Pressure Distribution Δp Results

yond the simple path of leakage between ring bores and rod, a characteristic often assessed with "light tight" checks on a plug gauge. Leakage can occur across faces that are not flat/coplanar. Leakage can occur in ring joints and along edges that do not form perfect corners.

Figure 3 illustrates the leak paths for a RTB sealing set, with the in-cup pressure loading shown in Figure 2. Joints in the radial and tangent rings are designed to accommodate bore wear yet still permit ring segments to maintain rod contact under loading from gas pressure. The back-up ring is not designed to wear and typically has a clearance of 0.008 and 0.010 in. (0.203 and 0.254 mm) between its inner diameter (ID) and the rod.

IN-CASE PRESSURE DISTRIBUTION

The instantaneous sealing performance of an individual ring set will change throughout the packing, causing the in-case pressure distribution to be variable. The intent of this section is to discuss the average pressure distribution looking at greater run times.

MEASURED RESULTS

Hoerbiger has a multipurpose test compressor (MPTC) at the research and development facility in Vienna, Austria. The MPTC is a highly instrumented reciprocating compressor used for a wide range of experiments, one of which was looking at the in-case pressure distribution of the packing case with four sealing sets. The test was run with a suction pressure of 20 bara (275 psig) and a discharge pressure of 40 bara (565 psig), with the Δp results seen in Figure 4. The measured results found that the first ring set seals the dynamic pressure (discharge to suction) and the last ring set handles the static sealing (suction to atmosphere).

The measured results agree with what is typically seen in the field during packing maintenance and inspection. The first and fourth ring sets are approaching or at their wear stops; the second ring set has little wear; the third ring set is worn because it took over the static seal when the fourth ring set was no longer effectively sealing.

EXPLANATION OF MEASURED RESULTS

The leakage between two flat surfaces is directly related to the surface disparities and the force pushing the surfaces together, as seen in Equation (1). The larger the differential pressure across a ring set, the greater the force and the smaller the available leakage path. If there is little to no differential pressure, then more gas can flow through the surface disparities.

$$\text{Leakage Area} \propto \frac{\text{Surface Disparity}}{\text{Force}} \tag{1}$$

While a compressor is running, the pressure oscillates between suction and discharge. The first ring set is directly exposed to this dynamic pressure, lightly gripping the rod when the chamber is at suction condition and gripping the rod progressively harder as the in-chamber pressure increases, shrinking the leakage area. This phenomenon causes the first ring set to seal all the dynamic pressure, allowing internal packing cups to equalize to suction pressure.

Since there are little pressure oscillations inside the packing, the ring set before the vent line is essentially a static seal. The differential pressure across this set is the delta between suction pressure and the vent-cup pressure.

PACKING LEAKAGE MODEL CREATION

The CompSIM simulation model was set up to match the MPTC compressor geometry and operating conditions. A detailed description of the simulation program CompSIM can be found elsewhere.[3]

The leakage paths on the packing rings are highly variable, but generally have a very small leakage area. For the purpose of this study, average leakage values were used to approximate packing leakage with a series of orifices. The simulation results can be seen in Figure 5. The modeled results agree with the simulation results. The first ring set handles the dynamic pressure, the second and third ring sets have almost no differential pressure, and the last ring set is sealing from the approximate suction pressure to the vent pressure of 0 barg.

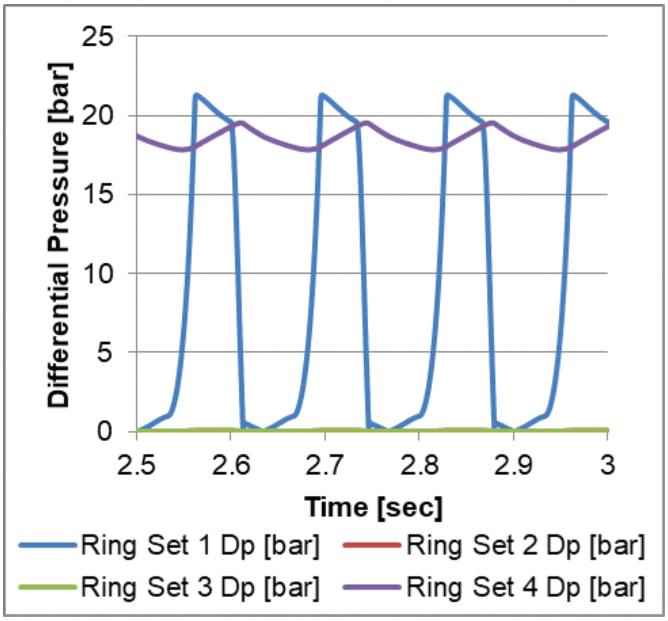

Figure 5. Differential Pressure [bar] Vs. Time [sec] Simulation Results

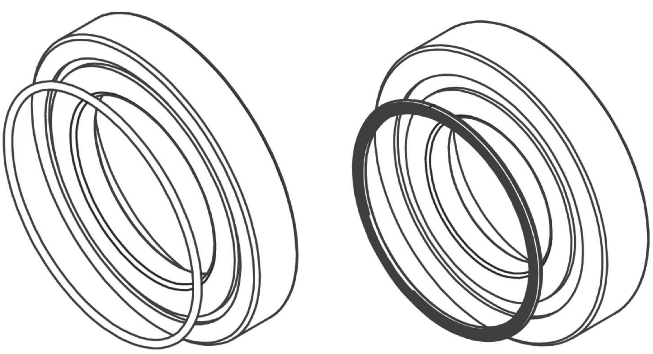

Figure 6. Round Wire Nose Gasket (Left); Flat Spiral-Wound Nose Gasket (Right)

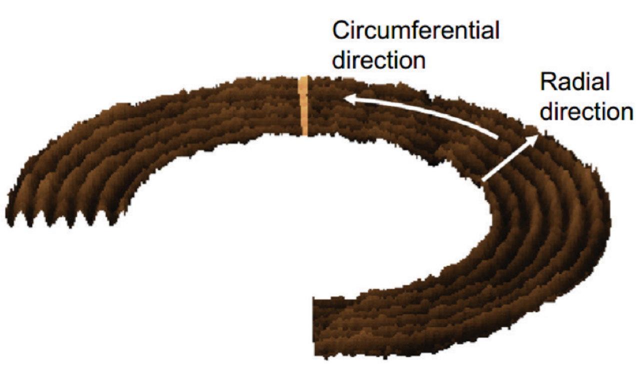

Figure 7. Cup-To-Cup Leakage Flow

PACKING CASE FUGITIVE EMISSIONS SOURCES AND REMEDIES

An optimized packing design will route all the gas leakage to the packing vent and to the disposal system. There are three leak paths that will allow the gas to bypass the rod packing vent and leak into the distance piece, assuming all the fittings are in working condition.

AROUND THE NOSE GASKET

The packing nose cup seals against the end of the stuffing box with the use of a gasket. The two most common nose gaskets are the round wire and the spiral-wound types, with examples seen in Figure 6.

LEAKAGE SOURCES

Reuse Of Nose Gasket

A gasket is designed to plastically deform (crush) under a certain clamping load, filling the surface irregularities (surface roughness) between mating surfaces. Upon reuse, the amount of plastic deformation is greatly reduced, decreasing the gasket's ability to fill the surface irregularities.

It is not always practical to pull the piston rod when new packing rings need to be installed, which often leads to reuse of the nose gasket.

Stuffing Box Counter Surface

Through the life of the compressor, the stuffing box counter surface will begin to degrade. Corrosion, deposits, and minor impressions from prior gaskets are all common surface issues. These surface irregularities can prevent creation of a gas tight interface between the gasket and counterface, resulting in leakage – particularly when gaskets do not always seat in the exact position as the prior gasket installation.

Gasket Misapplication

Nose gaskets are often made from aluminum, copper, iron, or stainless steel and are designed for a certain clamping load, process gas, and pressure. If the material is not compatible with the application, the gasket will not seal properly, resulting in leakage.

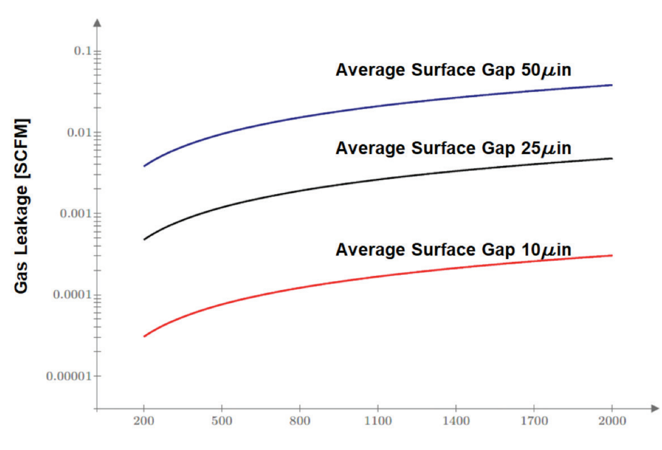

Figure 8. Cup-To-Cup Leakage Relative To Surface Roughness

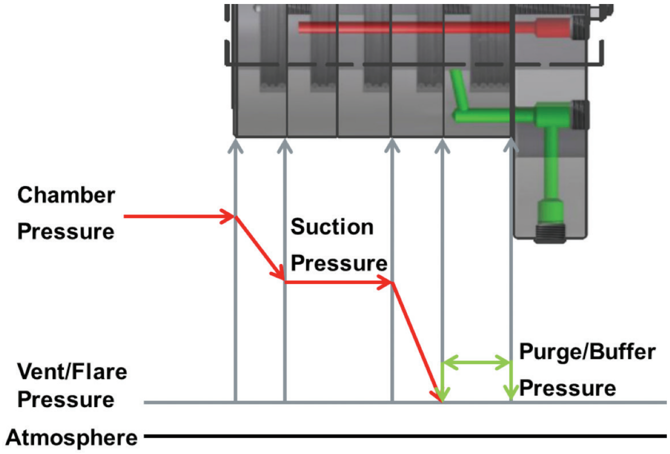

Figure 9. Ideal In-Case Pressure Distribution With Buffer Seal

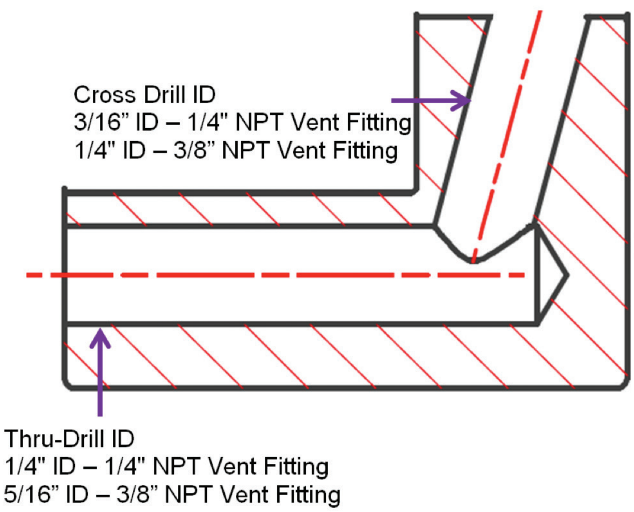

Figure 10. Vent Cup Geometry For 1/4-in. and 3/8-in. NPT Vent Lines

Cup-To-Cup Leakage

The leakage path between two flat surfaces is directly related to the force and size of the surface disparities, as discussed in Equation (1). However, there are practical limitations to the packing case clamping force and the packing cup flatness tolerance, meaning there will always be a leak path between the cups.

QUANTIFY CUP-TO-CUP LEAKAGE

The leakage gas will flow radially from the cup ID to the cup outer diameter (OD) with some circumferential flow to find the path of least resistance, illustrated in Figure 7. A well-manufactured cup will have a surface roughness of ~16 Ra (min) or better and a flatness of 4 to 10 light bands, dependent upon service.

Calculating the true flow path size is highly variable and is outside the scope of this article. Flatness, waviness, roughness, surface lay, and contact pressure distribution due to elastic behavior of the packing case are all factors that affect

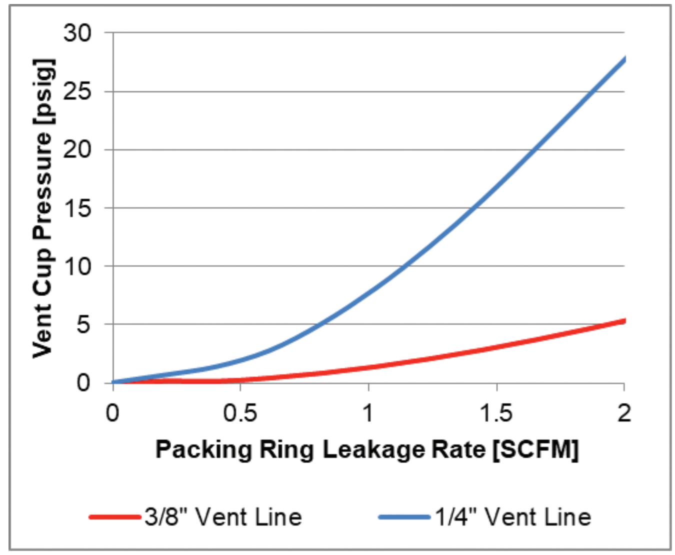

Figure 11. Vent Cup Pressure Vs. Packing Ring Wear

the cup-to-cup seal. However, a reasonable approximation to calculate the leakage area is to use half of the surface roughness and flatness as the average height, the "b" term in Equation (2).[4] Because of the low gas velocities and small length scales, the gas is assumed to be isothermal, allowing the use of Equation (2).[5]

For typical natural gas compressor operating conditions, a properly manufactured packing case will have between ~0.288 and ~3.744 SCFD of leakage per cup-to-cup joint. But, as the surface finish deteriorates, the leakage will increase by the power of three, as shown in Figure 8.

The only method to eliminate this leak path is with an O-ring seal at each cup-to-cup joint.

$$Q = \frac{4 \times \pi \, \Delta p \times b^3 \times p}{3 \times \mu \times \ln\left(\frac{r_{OD}}{r_{ID}}\right)} \qquad (2)$$

OUT THE BACK OF THE CASE

Packing vents are typically routed to a safe location or gas disposal system (i.e., flare stack) to control the compressor emissions. The vent cup should be at the same pressure as the disposal system, which is typically between 1 and 2 psig (0.069 and 0.138 bar). The distance piece should be at atmospheric pressure (0 psig), resulting in a slight differential pressure. This pressure differential is the driving force for gas leakage out of the back of the case. The packing case will either have a seal ring set after the packing vent or a buffer (purge) seal ring set to control the leakage into the distance piece. Figure 9 represents the ideal pressure distribution in a case with a buffer seal. The following sections will discuss how the case geometry impacts the effectiveness of these sealing sets.

VENT LINE CONFIGURATION CONSIDERATIONS

The vent line configuration is critical to keeping the in-case pressure to a minimum. In North America, packing cases vent lines will either have 1/4-in. or 3/8-in. NPT fittings. The ID of

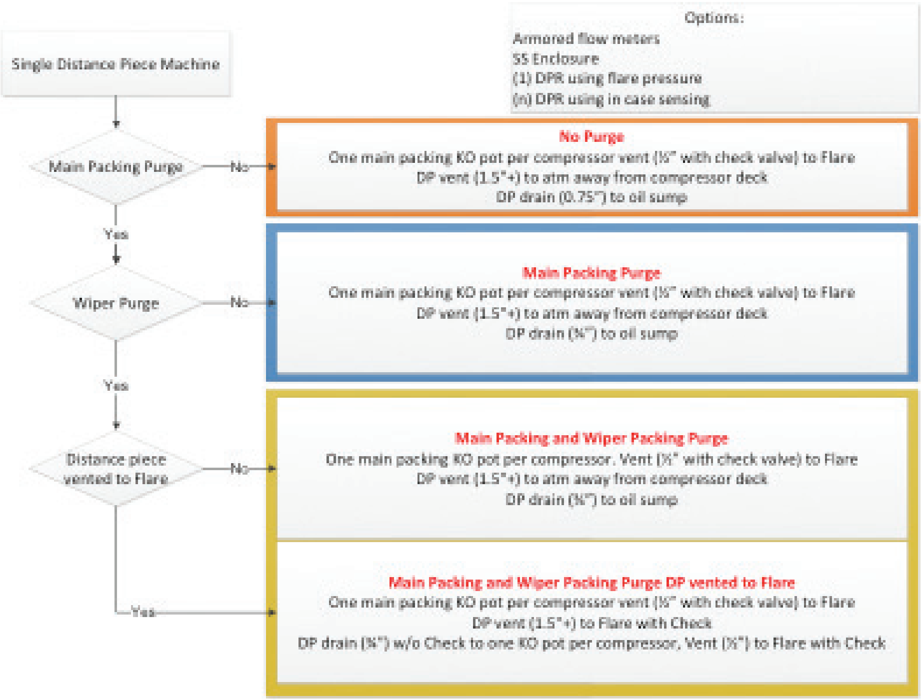

Figure 12. Single Distance Piece Selection Road Map

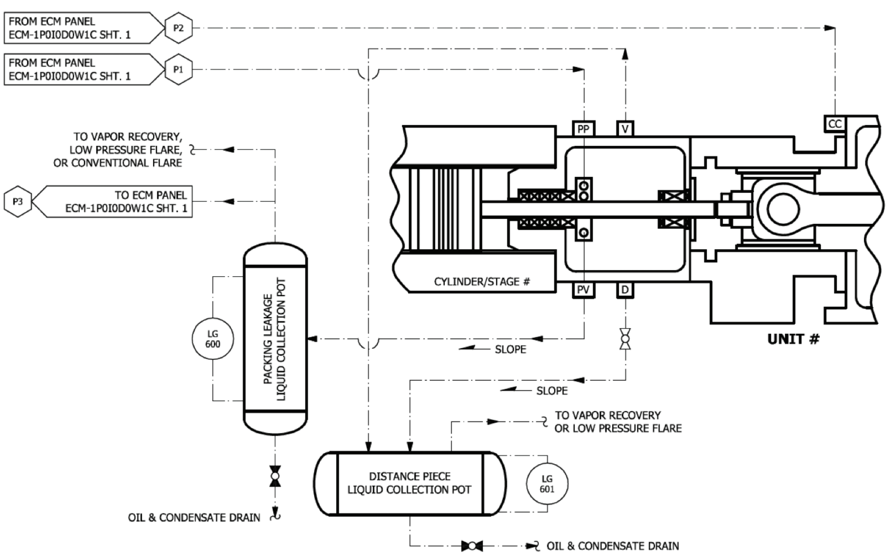

Figure 13. Ideal Single Distance Piece Vent And Drain Arrangement

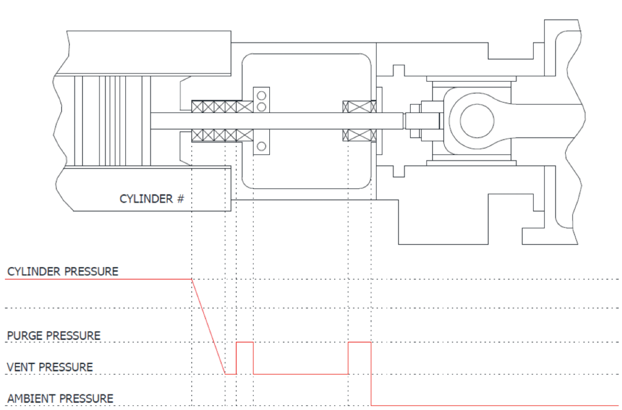

Figure 14. Ideal Single Distance Piece Pressure Distribution Along The Rod

1/4-in. and 3/8-in. tubes with typical wall thickness are 0.152 and 0.277 in. (3.861 and 7.026 mm), respectively. Common vent cup geometries are seen in Figure 10. Each of these flow channels poses a restriction on the gas leaving the packing vent cup. As the leakage flow continues to increase, so will the pressure drop through the flow restriction, causing increased in-cup pressure.

The packing case model from the "Vent Line Configuration Considerations" section was iterated to account for the packing ring wear over time and the impact on the vent cup pressure for 1/4-in. and 3/8-in. NPT vent lines. The results in Figure 11 demonstrate that the 1/4-in. vent line poses a significant flow restriction with a moderate amount of vent leakage.

Without A Buffer Seal

A packing case without a buffer seal at the back of the case will always have leakage into the distance piece. The amount of leakage is determined by the effectiveness of the vent seal rings and the in-case pressure.

With A Buffer Seal

Since gas will always flow from high pressure to low pressure, the only method to prevent leakage out the back of the case is to use a buffer seal with a pressure greater than the vent cup pressure. The typical buffer seal is ~15 psig (1.034 bar), but as seen in Figure 11, even a slight increase in the packing leakage area can cause the in-cup pressure to increase above 15 psig, negating the effectiveness of a fixed pressure buffer system.

To ensure the buffer pressure is always greater than the vent cup pressure, the buffer pressure should be controlled with a bias regulator. The bias regulator should receive feedback from an in-case sensing line. An in-case sensing line will have no gas flow through it, meaning no pressure drop, allowing the bias regulator to accurately react to the true in-cup condition.

DISTANCE PIECE VENT AND DRAIN ARRANGEMENTS AND IMPLEMENTATION ROAD MAP

The distance piece vent and drain arrangement is critical for controlling the emissions on and around the compressor deck. A properly configured

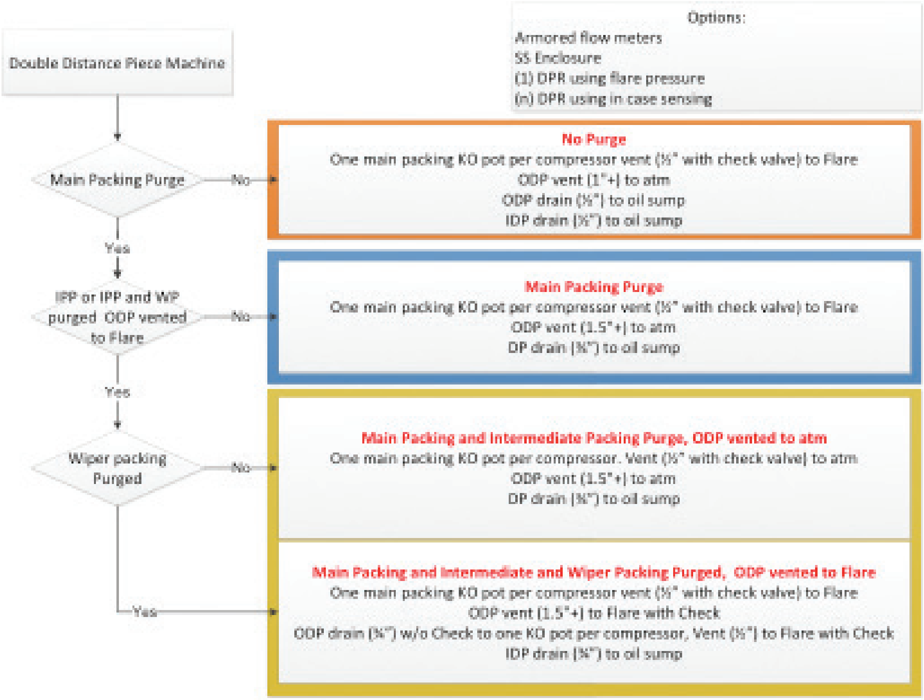

Figure 15. Double Distance Piece Selection Road Map

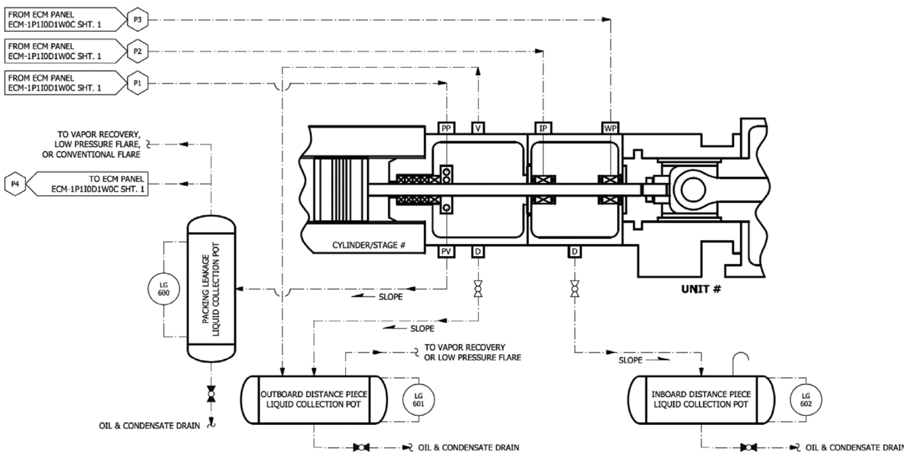

Figure 16. Ideal Double Distance Piece Vent And Drain Arrangement

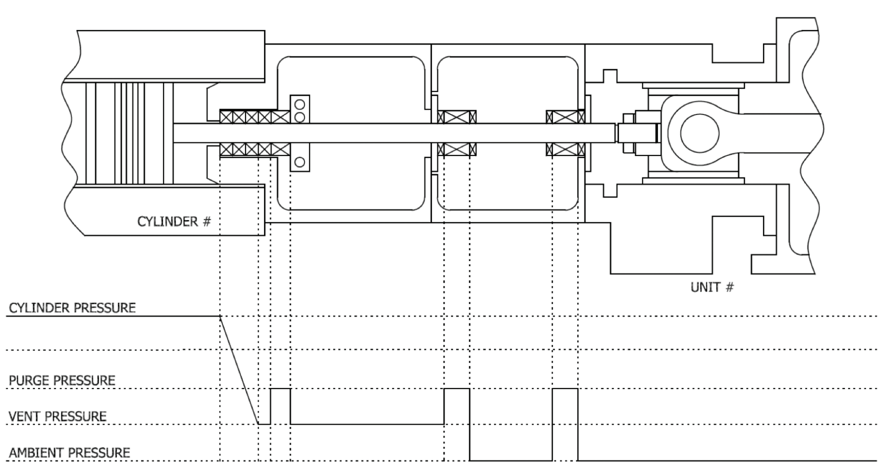

Figure 17. Ideal Double Distance Piece Pressure Distribution Along The Rod

system will route the emissions to the desired location, ensuring operator safety and promoting environmental compliance.

The intent of this section is to provide an implementation road map on how to best arrange vent and drain systems. The road map is based on compressor configuration, available connections, and whether nitrogen is available at the site.

SINGLE DISTANCE PIECE VENT AND DRAIN ARRANGEMENT

Figure 12 outlines the four different levels a single distance piece machine can be configured to mitigate fugitive emissions onto the compressor deck, with the optimal configuration (Level 4) seen in Figure 13.

Figure 14 outlines the pressure distribution along the rod for the optimal configuration. Moving from left to right, the main pressure packing will minimize the leakage along the rod but as discussed above, some process gas can leak around the main pressure packing, into the distance piece. This gas can then continue to migrate into the crankcase of the machine. A purged wiper packing will create the same nitrogen pressure buffer as the main packing, mitigating process gas leakage ingress into the crankcase, allowing all emissions to be routed to the desired location, commonly the flare header.

DOUBLE DISTANCE PIECE OF SELECTION ROAD MAP

The optimal configuration of double distance piece machines is similar to single distance piece machines but there is the ability to have three purged seals, further mitigating the chance of fugitive emissions. Figure 15 outlines how the four different levels a double distance piece machine can be configured to mitigate fugitive emissions onto the compressor deck with the optimal configuration (Level 4) seen in Figure 16.

Figure 17 outlines the pressure distribution along the rod for the optimal configuration. Moving from left to right, the main pressure packing will minimize the leakage along the rod but as discussed above, some process gas can leak around the main pressure packing, into the distance piece. This gas can then continue to migrate into the crankcase of the machine. A purged intermediate and wiper packing will create the same nitrogen pressure buffer as the main packing, mitigating process gas leakage ingress into inboard distance piece and the crankcase, allowing all emissions to be routed to the desired location, commonly the flare header.

CONCLUSIONS

Fugitive emissions from the piston rod sealing systems pose a significant environmental and safety risk as one of the primary emitters in the natural gas supply chain. The article identifies the three pressure packing leakage sources and provides the following solutions:

- Around the nose gasket due to gasket misapplication, poor stuffing box surface finish, or the reuse of the nose gasket.
  - Ensure the gasket is compatible with given operating conditions and packing case design.
  - Inspect the finish of the stuffing box during each service event and repair as needed.
  - Whenever possible, use a new nose gasket to minimize chance of leakage.
- Cup-to-cup leakage quantity is dependent on the surface finish and clamping load.
  - To minimize cup-to-cup leakage, ensure all cup faces are parallel with as little roughness as possible.
  - The only means to eliminate cup-to-cup leakage is with the use of an O-ring at each cup joint.
- Out the back of the case – due to high vent back pressure or lack of buffer seal.
  - The use of a buffer (purge) seal at the rear of the packing case is the only means to prevent leakage out of the back.
  - However, poor vent system design can cause the vent cup pressure to exceed the buffer pressure, negating the effectiveness of the buffer seal.
  - The vent tubing and vent cup should be designed to minimize back pressure creation.

Since each compressor and facility will be configured differently, the road maps in the "Conclusions" section were created to provide guidance for the optimal configuration to minimize the chance of fugitive emissions.

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