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Application Note

Monitoring strategy – Effective cylinder leak detection using polytropic exponent function

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ABSTRACT

The need for reliably detecting reciprocating compressor cylinder leaks is paramount as the cylinder, and more specifically the valves, account for the majority of the maintenance for these machines. PV plots are often used to determine cylinder leaks but these cannot be readily monitored to alarm limits automatically and require specialists to analyze and interpret the results. The polytropic exponent function provides much of the same cylinder leak information as the PV plot but with complete automatic monitoring capability and without requiring much specialist expertise.

Reciprocating compressor maintenance

Reciprocating compressors play a vital role in the petrochemical industry. These machines are used in critical applications just like their centrifugal and axial compressor counterparts but are much less monitored, despite the fact that they are more maintenance intensive. Cylinder leaks, which account for a large portion of the machine failures, are shown in Figure 1. Leaks reduce cylinder capacity and in some cases require greater compressor work. Valves account for most of the cylinder leaks.

Cylinder leak monitoring techniques

A number of monitoring techniques are currently available to detect cylinder leaks, but their accuracy for detecting and locating the source of the leaks varies, as does the cost of implementation. The practicality of using the various leak detection functions depends on a number of factors such as machine configuration, process, existing monitoring system, etc. A list of some of the most used techniques is shown in Table 1.

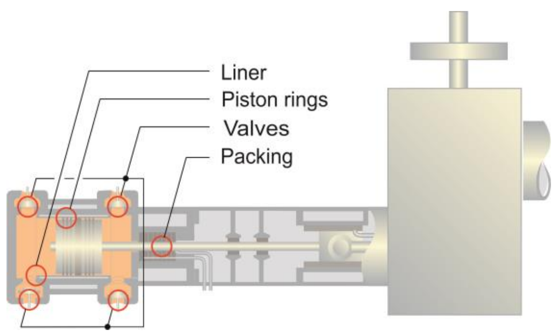

Figure 1. 2-cylinder reciprocating compressor shown, indicating where cylinder gas leaks can occur. The area in the cylinder where the compressed gas is located is shown in orange.

The PV plot, pressure vs. crank angle and the polytropic exponent function, all based on dynamic pressure measurements in the cylinder chamber triggered to the piston/volume displacement, provide the greatest accuracy for detecting specific gas leaks in the cylinder, when properly configured. However only the polytropic exponent function doesn't require a high level of user expertise to diagnose the same faults.

PV plot – forerunner to the polytropic exponent function

The pressure-volume plot (PV plot) together with the calculated theoretical PV plot, as shown Figure 2, is closely related to the polytropic exponent function. The PV plot is based on measured dynamic pressure values in the cylinder that are plotted against the corresponding calculated

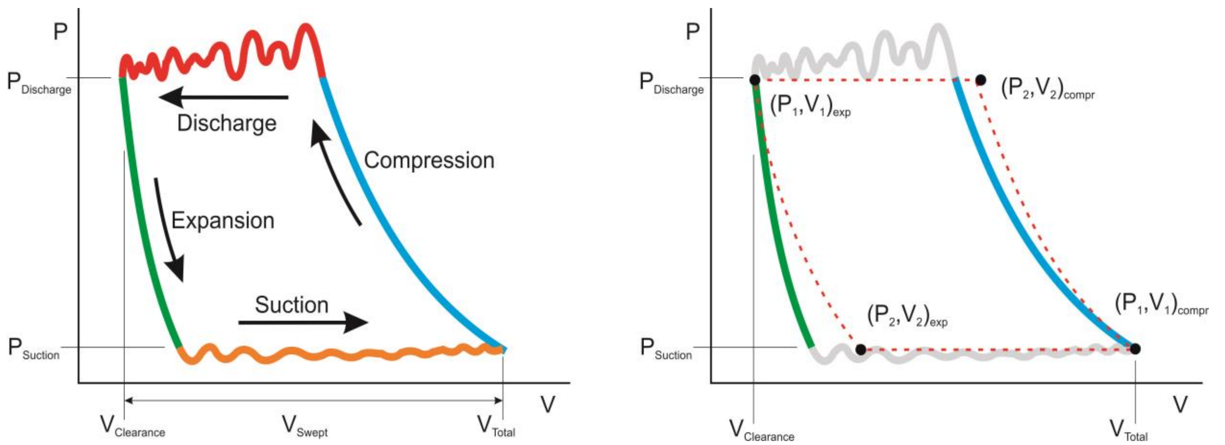

Figure 2. Left: PV plot showing the four basic compressor cycles. Right: Theoretical PV plot (red) overlying a PV plot. The deviation between the theoretical and actual expansion and compression curves indicate a suction valve leak in this example.

displaced volume values at different intervals of crank rotation.

The PV plot is used for detecting cylinder leaks by comparing the measured expansion and compressor lines (the green and blue sides of the plot, respectively, shown in Figure 2 on the left) to the theoretical PV plot calculations (the red lines shown in Figure 2 on the right). The PV plot can also be used for identifying valve and process problems (the top and bottom parts of the PV plot), often before a leak occurs.

Although the PV plot is accurate and reliable for detecting cylinder leaks if properly set up, it requires a specialist to visually observe deviations to detect a leak because these cannot be easily monitored automatically. This is costly from a service perspective. What is needed is a method for converting the PV plot expansion and compression curves into a scalar values that can be automatically monitored to alarm limits.

Polytropic exponent function

The polytropic exponent function is very similar in concept to the theoretical PV plot that overlies measured PV values. Both functions are used for identifying changes in the expansion and compression processes, which would be indicative of a cylinder gas leak at a specific location, except the polytropic exponent function does all of this automatically. Therefore it is not necessary to visually look at PV plots on a regular basis to detect

Measurement technique	Leak location detection
Valve temperature	Only the specific valve it is mounted on
Leak flow/temperature	Only the packing
Discharge gas temperature	Unknown
Maximum cylinder pressure	Unknown
Compression ratio	Unknown
Flow balance	Unknown
Packing temperature	Only the packing
Gated cylinder head vibration	Only the valves, piston rings
Volumetric efficiency	Only the suction valve, packing, discharge valve (and maybe piston ring)
PV plot, pressure vs. crank angle	Suction valve, packing, discharge valve, piston ring
Polytropic exponent function	Suction valve, packing, discharge valve, piston ring

Table 1. Monitoring techniques for detecting cylinder leaks.

leaks as is done with PV plots.

The polytropic exponent function (and the theoretical PV plot), is based on a thermodynamic closed system where the change in internal energy of the system is based on the work (pressure-volume)/heat transfer done on the gas during the compression and expansion cycles. There is no heat or mass flow added during this process. This process is best described by the thermodynamic polytropic relation (Equation 1), which takes place between two states:

Where: $P_1V_1^n = P_2V_2^n$ = Constant

P = Pressure

V = Volume

n = Polytropic exponent (constant)

The polytropic exponent n, which can take on many values (hence the term polytropic), is directly related to the properties of the gas being compressed or expanded. This expression is used for plotting the theoretical pressure-volume, which overlays the measured PV plot as shown in Figure 2.

Equation 1 can be solved for the polytropic exponent n as follows:

$$n = \frac{ln(P_2) - ln\,(P_1)}{ln(V_1) - ln(V_2)}$$

The polytropic exponent function shown in Equation 2 uses the actual measured pressure values and corresponding volume values to calculate the polytropic exponent value n for a given segment or segments on the expansion and compression lines, as shown in Figure 4.

Changes in the scalar value of the polytropic exponent n of the four segments shown in Figure 4 can give an indication if there are cylinder leaks and where they are occurring, assuming there are no changes in the gas properties or process conditions. This is shown in Figure 5. These values of course can be automatically monitored to alarm limits.

An actual example of the polytropic n values for a re-injection reciprocating compressor is shown in Figure 6, but without leaks.

Faults that can be detected

The polytropic exponent function can detect the following:

- Delay in opening and closing of valves (e.g. sticking valves)
- Valve throttling, fluttering
- Gas leaks in the cylinder due to valves, piston rings, cylinder liner or packing

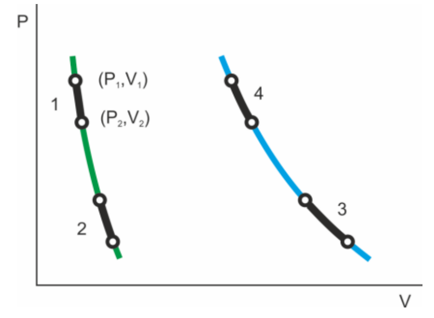

Figure 4. Example of locations for calculating n for four segments using Equation 2. The P and V values for segment 1 are indicated on the expansion line. (Green is the expansion line, blue is the compression line).

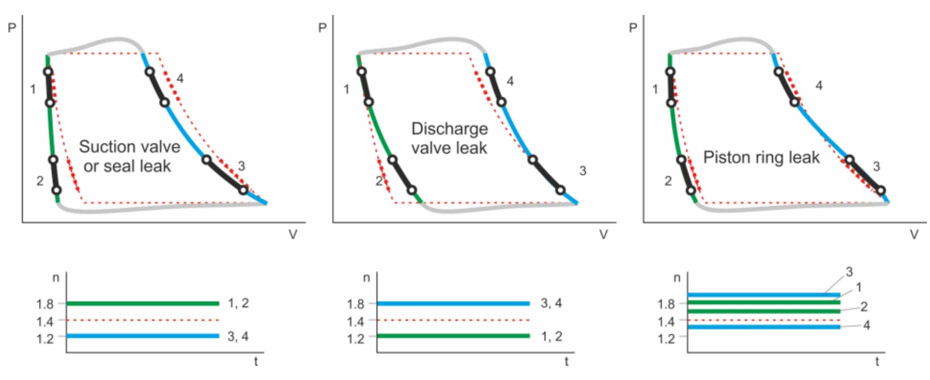

Figure 5. Examples of detecting cylinder leaks (shown in the PV plots), using the four calculated polytropic n values (shown below the PV plots). The theoretical PV plot is shown as a red dotted line, where n = 1.4 (based on the gas properties).

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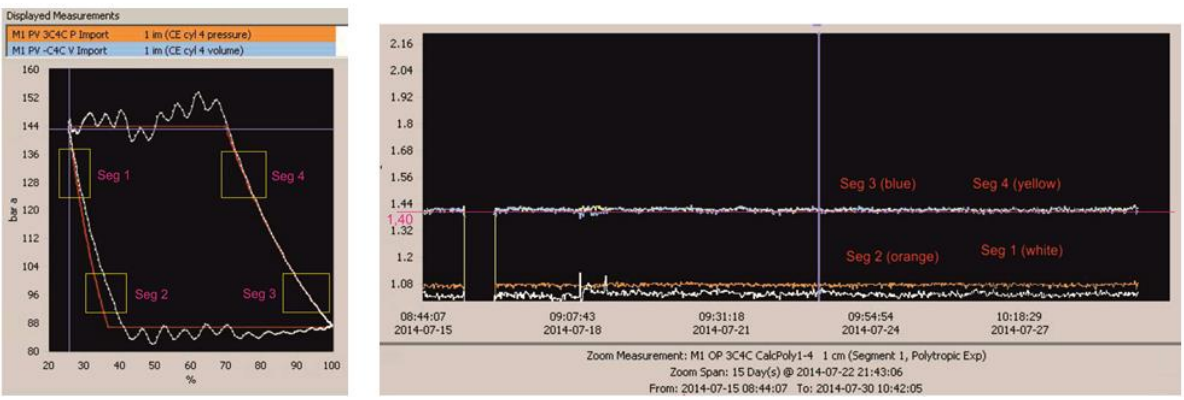

Figure 6. Cylinder 4 CE (stage 1) of a 2 stage, 2 cylinders per stage, double acting reciprocating compressor for gas compression (4 cylinders in total. The expansion line deviation is due to acoustic resonance of the dynamic pressure sensor, not due to a leaking valve.

In addition to detecting cylinder leaks or sticking valves, the polytropic exponent function is sensitive to other process conditions that can give an error if not taken into account. These include process pressure pulsations, liquids in the gas stream, changing gas composition, capacity control, and changing suction and discharge pressures and temperatures of the gas.

Disadvantages of using dynamic pressure sensors in the cylinder

The polytropic exponent function is a very reliable, accurate measurement but the accuracy of dynamic pressure sensors used for the polytropic exponent function, the same used for PV plot and the rodload calculations, is very dependent on the sensor location. A significant error can occur if the one or more of the following conditions are present at the sensor location:

- **Gas flow turbulence** – Sensor is mounted near an area of gas recirculation or turbulence
- **Acoustic resonance** – Sensor is mounted at the end of a tube
- **Pressure drop** – Pressure gradient exists near sensor around the valve inlet and outlets
- **Heat transfer** – Compression chamber wall temperature near sensor is hotter than suction gas
- **Measurement Synchronization** – The tacho pulse has to be precisely synchronized to the pressure measurements

The accuracy of the calculations is also highly dependent on how precisely the clearance volume has been determined (especially if it is adjustable).

Conclusion

Based on the results obtained by monitoring a re-injection gas compressor, it can be concluded the polytropic exponent function, when properly set up, provides very stable and reliable measurements. Even with the presence of acoustic resonance within the pressure sensor channels, the measurements are sufficient for machine condition monitoring. It is not the absolute values of n that have interest, but the ability to detect changes in these values. The polytropic exponent function and PV plot are some of the most effective measurement techniques for detecting reciprocating compressor cylinder leaks, but the big difference between the two is that the polytropic exponent function can be monitored automatically. When an alarm limit is exceeded, service can be cost-effectively planned ahead of time and the necessary parts ordered long

before the machine has to be opened. Only when the alarms have been exceeded is it necessary to use a specialist to analyze the PV plots, if this person is at all needed.

It is important to understand that the polytyropic exponent function is not intended to replace the PV or pressure vs. crank angle plots. It is intended only to compliment these plots as way of reducing the specialist's work load concerning monitoring and diagnosing cylinder gas leaks. Furthermore, the polytropic exponent function, much like the theoretical PV plot, only provides information on the expansion and compression processes of the compressor, not on the discharge and suction processes like the measured PV plot does. Important information on the condition of the valves can also be seen in the suction and discharge processes, therefore the polytropic exponent function is not intended to replace the PV plot, only compliment it.

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