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Condition monitoring and diagnostics of machines — Reciprocating compressors

Surveillance et diagnostic d'état des machines — Compresseurs alternatifs

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Foreword

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This document was prepared by Technical Committee ISO/TC 108, *Mechanical vibration, shock and condition monitoring*, Subcommittee SC 5, *Condition monitoring and diagnostics of machine systems*.

Any feedback or questions on this document should be directed to the user’s national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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Introduction

Reciprocating compressors have been used in industry long before centrifugal, axial and other types of compressors were invented and they are still being used today. In fact, reciprocating compressors have a special niche in the industry that cannot be matched by other types. These are applications where precise, efficient high-pressure gas delivery is needed with low flow rates in comparison with turbo-compressors. This is made possible by the positive displacement compression action of reciprocating compressors. The compressor's efficient flexibility is essential for variable process conditions such as for multiple-stream compression and for gases that vary in molecular weight. They are able to generate high pressure ratios independent of the density of the gas and are very flexible to control the flow capacity. In the hydrocarbon processing industry, the reciprocating compressor is ideal for low molecular weight gases such as hydrogen (H_2).

Reciprocating compressors are increasingly important in refinery processes (e.g. hydrotreating, hydrocracking, isomerisation and catalytic reforming) many of which are intended for producing cleaner fuels. There are many industrial applications today that require this type of compression and this requirement will continue to be important well into the future. This is especially true in future energy transition processes such as midstream transport and storage, where pure hydrogen or a blend of hydrogen with natural gas will become an important energy carrier.

The reciprocating compressor successfully fulfils those process requirements for which it is intended, but they present a challenge with regard to maintenance. As a result of the many moving parts (rotation and translation) and the high-dynamic forces and moments caused by the reciprocating movement (including pulsation-induced forces and cylinder gas forces, also called cylinder stretch forces), there is a higher incidence of wear, leakage and breakage compared to the centrifugal compressor. The extra maintenance and downtime incurred by reciprocating compressors, both planned and unplanned, can represent a critical bottleneck to process production, if not properly managed.

Because of their design, reciprocating compressors will always require more maintenance (e.g. replacing compressor valves, piston rings, rider bands and packing) than a comparable turbo-compressor. Therefore, effective condition monitoring and diagnostic strategy plays an extremely important role in reducing downtime and life cycle costs of these machines while increasing reliability, safety, integrity and efficiency.

Traditionally, however, the reciprocating compressor is often less monitored or incorrectly monitored compared to other critical plant machinery. This is partly due to the difficulty of detecting and diagnosing the unique potential failure modes associated with the compressor's reciprocating action caused by the dynamic loads already described. From a vibration perspective, many machine faults manifest themselves as impacts (i.e. short duration non-stationary peaks or peaks that occur only at approximate specific crank angles). Consumable component wear is difficult to monitor directly and therefore requires the use of specialized measurement techniques as does cylinder trim leak detection and diagnosis. Pressure and flow-induced pulsations due to the reciprocating action can distort the raw signals, therefore not only are specialized measurement techniques required, but also expertise in interpreting the results.

In general, there is less understanding of the condition monitoring and diagnostic requirements of reciprocating compressors compared to other machines and there has been a lack of standards to fill this void. Existing standards such as ISO 13631, ISO 20816-8, API STD 618 and API STD 670 deal with design, procurement, installation and protection of the reciprocating compressors but very few of them address condition monitoring and diagnostics.

Emission regulations have recently become more stringent, therefore monitoring gas leakage to the atmosphere is briefly mentioned in this document.

The CM and diagnostic strategy and techniques described in this document apply to reciprocating compressors with many different machine configurations (e.g. number of stages, speed range, cylinder lubrication, capacity control and cylinder cooling) and is used in many different industrial applications.

However, from a cost benefit perspective, this document is most relevant to critical, possibly single-line machines instead of standby machines and/or units that have an output over 1 000 kW.

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The vast majority of these types of reciprocating compressor are used in the hydrocarbon and chemical processing industries and natural gas transport and storage facilities. As these machines are used extensively in the upstream, midstream and downstream oil and gas industries, the focus will be on these applications but this by no means excludes critical applications in other industries.

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Condition monitoring and diagnostics of machines — Reciprocating compressors

1 Scope

This document focuses on recommending condition monitoring (CM) techniques for detecting and diagnosing developing machine faults associated with the most common potential failure modes in reciprocating compressors.

This document is intended

a) to set out a reliable and effective CM approach for reciprocating compressors,

b) to create a mutual understanding of the criteria for successful reciprocating compressor CM and to foster cooperation between the various application stakeholders,

c) for use by end-users, contractors, consultants, service providers, machine and part manufacturers and instrument suppliers,

d) as the reciprocating compressor design, its operation and maintenance regime can be very different from one application to the next, it is important to highlight that condition monitoring and diagnostics method described in this document is reference guidelines and non-mandatory information, and

e) To make this standard more effective, it is required to actively share the operation and condition data of the reciprocating compressor among the relevant parties.

Some of the reciprocating compressor types covered by the requirements of this document include:

f) slow (under 600 r/min) and moderate speed (600 r/min to 1 000 r/min) machines manufactured and procured in accordance with the requirements of API STD 618;

g) high-speed and pre-packaged machines (over 1 000 r/min) on a skid that are manufactured and procured in accordance with the requirements of ISO 13631 or API SPEC 11P;

h) hyper compressors used for secondary ethylene compression in low density polyethylene (LDPE) production;

i) lubricated and non-lubricated machines;

j) water-cooled and gas-cooled machines;

k) horizontal, vertical V-type, L-type and W-type machines;

l) horizontal, vertical machines with piston rings and those with labyrinth seal pistons (vertical machines only);

m) single-acting and double acting machines;

n) machines with a tandem cylinder configuration;

o) single and multi-stage compression machines;

p) machines with and without capacity control;

q) ring, poppet, reed and plate valve type machines;

r) machines mounted on flexible and rigid structures;

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s) machines driven by electric motors, gas and diesel engines, turbines (with or without a gearbox) all with a flexible or rigid coupling;

t) integral gas-engine-driven machines (engine portion out of scope);

u) offshore applications (e.g. platforms, FPSOs (floating production storage and offloading), FLNGs (floating liquified natural gas), FPU (offshore foating production unit) and fixed installations).

This document focuses on the compressor itself (cylinders, distance pieces, crosshead, frame and all internal parts) and not on the prime mover or the external systems (e.g. piping, scrubbers, pulsation vessels, and pulsation control devices). Only brief mention is made of monitoring the foundation, skid and pedestal.

The scope does not include requirements for monitoring the auxiliary systems (e.g. for lubrication, cylinder cooling, intercoolers and gas purging), but process parameters from these systems are often monitored.

The scope does not cover installation analyses of systems either, (e.g. pulsation and mechanical response and thermal analysis of the piping).

This document covers online (permanently installed) and portable instrument CM and diagnostic techniques for operating reciprocating compressors.

Machine testing, which is only done during shutdown, although very important, is not part of the scope of this document, nor is the one-time acceptance and performance testing.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

API STD 618, *Reciprocating Compressors for Petroleum, Chemical, and Gas Industry Services*

3 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

3.1
machine state
operational process or duty cycle of the reciprocating compressor

EXAMPLE Stopped, unloaded, loaded, capacity control (variable frequency drive, valve unloading, clearance pockets and recycling), change of speed, change of suction and/or discharge conditions and change of gas properties.

3.2
descriptor
data item derived from raw or processed parameters or external observation

[SOURCE: ISO 16079-1:—, 3.4]

Note 1 to entry: Descriptors are used to express symptoms and anomalies. The descriptors used for monitoring and diagnostics are generally those obtained from condition monitoring systems. However, operational parameters, like any other measurement, can be considered as descriptors.

Note 2 to entry: Descriptors are also referred to as "condition monitoring descriptors".

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3.3
prime mover
engine, motor or turbine that drives the reciprocating compressor

3.4
monitoring technique
measurement or set of *descriptors* (3.2) used to detect a *potential failure mode* (3.12) or provide diagnostic information on the type of fault that has occurred, its location and severity

3.5
crank throw
portion of crankshaft that connects to a single or tandem cylinder

Note 1 to entry: Also refers to the entire cylinder and distance piece assembly connected to the crankshaft.

3.6
stroke
distance travelled by the piston from TDC to BDC, or vice versa

Note 1 to entry: In quantitative terms, it is the crank rotation diameter or crank radius × 2.

3.7
rod reversal
change in direction of force in the piston rod/crosshead pin loading (tension to compression or vice-versa), which results in a load reversal at the crosshead pin during each revolution

[SOURCE: ISO 13631:2002, 3.14, modified — "/crosshead" has been added.]

3.8
tail rod
rod extension from piston on head end side of cylinder (HE) to ensure equal volume displacement on both sides of piston for more equal loading as well as provide optimal piston alignment

3.9
tandem cylinder
arrangement of at least two pistons on the same rod moving in separate chambers in the same cylinder

[SOURCE: ISO 5598:2020, 3.2.753]

Note 1 to entry: The order of the large and small pistons on the rod depends on the application.

3.10
combined rod load
algebraic sum of gas load and inertia force on the crosshead pin

[SOURCE: API STD 618:2024, 3.7]

Note 1 to entry: Gas load is the force resulting from the differential gas pressure acting on the piston differential area. Inertia force is the force resulting from the acceleration of the reciprocating mass. The inertia force with respect to the crosshead pin is the summation of the products of the reciprocating masses (piston and rod assembly, and crosshead assembly including pin) and their respective acceleration.

3.11
crosshead
mechanical joint that converts rotary motion of the crankshaft into a reciprocating motion of the piston and piston rod with minimal friction

3.12
potential failure mode
change in condition of a reciprocating compressor component that can be detected by measurements that indicate an incipient fault is developing, which will eventually lead to failure

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3.13
crank angle reference sensor
reference speed and phase sensor or a crankshaft position sensor, that generates at least one pulse per crank revolution, which is used for determining machine speed and for synchronizing one or more *descriptors* (3.2) to crank angles

Note 1 to entry: Different types of sensor (displacement, inductive and optical sensors) with different types of output are used for this purpose.

Note 2 to entry: API STD 670 specifies displacement sensors for protection systems.

3.14
indicated power
brake power multiplied by η_{mech}

Note 1 to entry: It also represents the total area enclosed in a *pV* diagram times the speed.

3.15
brake power
power delivered by the *prime mover* (3.3) to supply the indicated power for the cylinder and compensate for frictional losses

Note 1 to entry: to entry; It is also the ratio of the indicated power to η_{mech}.

Note 2 to entry: Frictional losses are the sum of indicated power and friction power.

Note 3 to entry: Brake horsepower of a reciprocating compressor is the power measured using a brake type (load) dynamometer at the crankshaft.

3.16
adiabatic power
power required for isentropic compression and expansion within the cylinder chamber

3.17
friction power
power lost due to rider band and piston ring friction on the liner, packing friction, crosshead pin friction and the connecting rod bearing and main bearing friction

3.18
prognostics
analysis of the symptoms of faults to predict a future condition and remaining useful life

[SOURCE: ISO 6781-1:2023, 3.1.20]

Note 1 to entry: This can be a data-driven or model-based prediction model where loading conditions are continuously monitored.

3.19.1
volumetric efficiency
<theoretical definition> ratio of the actual gas volume displaced by the piston during discharge and suction and discharge to the swept volume

Note 1 to entry: There are two values for this, one each for discharge and suction.

3.19.2
volumetric efficiency
<measurable definition> ratio of the stroke distance when the valves are open to the total piston displacement-stroke

Note 1 to entry: There are two values for this, one each for discharge and suction.

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