International Journal of
Thermodynamics and Chemical Kinetics
ISSN 2456-6977
Volume 10, Issue 2, 2024
DOI (Journal): 10.37628/IJTCK
https://chemical.journalspub.info/index.php?journal=JTCK
Research IJTCK

Evaluation of Reciprocating Compressor Components: Failures and Downtime

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Abstract

The investigation on the evaluation of reciprocating compressor component failures using the reliability approach was examined for a period of five years. The components monitored were valves, seals, pistons, bearings, O-rings, and cylinders and the numbers of failure per year were obtained as 10, 8, 2, 7, 9, and 4 for the first year, 6 6, 2, 5, 7, and 2 for the second year, 7, 6, 2, 3, 7, and 3 for the third year, 5, 5, 1, 4, 5, and 2 for the fourth year and 5, 4, 1, 3, 4, and 1 for the fifth year with total number of failures 33, 29, 8, 22, 23, and 12, respectively. This investigation covers from 2016 to 2020 with order of failures as 33 (values)> 29 (seal)> 23 ("O"-rings)> 22 (Bearing)> 12 (cylinders)> pistons. The total downtime per year was evaluated and the obtained result revealed 4209.87 hours for the first year, 3355 hours for the second year, 14622.34 hours for the third year, 13358.37 for the fourth year, and 5582.65 hours for the fifth year as well as corresponding mean downtime of 105.25, 119.83, 52223, 607.20, and 310.15 hours. The reciprocating compressor failure and downtime can be attributed to lack of maintenance as well as over-utilization and indeed constant failure can be related to checking to ascertain the root cause of the component failure and this increased the downtime maintenance of the operation, The trend of the failures was monitored and the downtime as well and measures to control the occurrence was also put in place since the root cause of the failures were identified.

Keywords: Evaluation, reciprocating, compressor, components, failures, downtime

INTRODUCTION

The compressor is a device used to increase the pressure of compressible fluid, either gas or vapor, by reducing the specific volume of the fluid during the passage of the fluid through the compressor [1–2]. The compressors used to compress the Natural Gas (NG) into Compressed Natural Gas (CNG) are called gas compressors [3]. Compressors are invariably used for all applications which require pressurized air. One of the basic aims of compressor usage is to compress the fluid and then deliver it to a higher pressure than its original pressure [4]. The inlet and outlet pressure levels vary from a deep vacuum to a high positive pressure, depending on the required process necessity [5]. This inlet and outlet pressure is compared corresponding with the type of compressor and its configuration. Reciprocating compressors generally have a piston–cylinder arrangement where displacement of the piston in the cylinder causes a rise in pressure [6]. Reciprocating compressors are capable of giving large pressure ratios, but the mass handling capacity is limited or small [7]. Reciprocating

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Received date: September 26, 2024
Accepted date: October 26, 2024
Published date: November 15, 2024

Citation: Ukpaka C. P., Adeusi T. E., Nkoi B. Evaluation of Reciprocating Compressor Components Failures and Downtime. International Journal of Thermodynamics and Chemical Kinetics. 2024; 10(2): 12–22.

compressors may also be single-acting compressors or double-acting compressors. A single-acting compressor has one delivery stroke per revolution while in double-acting there are two delivery strokes per revolution of crankshaft [7].

Reciprocating compressors are key equipment widely used in oil extraction, gas production, oil refining, chemical industries, refrigeration, and gas transmission pipelines. In many industrial applications, variable loads are common for a reciprocating compressor, which is normally designed for the anticipated peak load [8]. Reciprocating compressors have mainly been used for the transport and further processing of fossil raw materials and for manufacturing their derivates – key industries that made no visible contribution to environmental protection [9]. However, since the range of applications for compressors was extended by regenerative energies in recent years and contributed to resource-saving energy production, they occupy the field of sustainable technologies in machinery and plant manufacture positively [10–11]. Their depiction in photovoltaics and biogas feed proves even more that they have long since occupied their permanent place for the provision and use of environmentally friendly energies. However, they can only contest this importance by using innovative techniques [12]. Reciprocating compressors have always played a pioneering role when implementing demanding market requirements, the same also applies to low emissions. They have met this postulate for several decades in both the oil and chemicals industries due to the compression of H_2 and H_2 gaseous mixtures in systems for hydride sulfurization (HDS) and recycling flare gas in refineries [13].

Reciprocating compressors generally have a piston–cylinder arrangement where displacement of the piston in the cylinder causes a rise in pressure [14]. Reciprocating compressors can give large pressure ratios, but the mass handling capacity is limited or small. Reciprocating compressors may also be single-acting compressors or double-acting compressors. The single-acting compressor has one delivery stroke per revolution while in double-acting there are two delivery strokes per revolution of the crankshaft [15].

A reciprocating compressor has a piston that moves downwards thus reducing pressure in its cylinder by creating a vacuum. This difference in pressure forces the suction chamber valves to open and bring gas or air in. When the cylinder goes up, it increases pressure thus forcing the gas or air out of the cylinder through a discharge chamber. Reciprocating compressors are used in a variety of industries and for different purposes. The following are the main applications of reciprocating compressors:

i. NG processing and delivery;
ii. chemical plants;
iii. oil refineries;
iv. refrigeration technology.

Reciprocating compressors are machines, which are widely employed in a variety of diverse industrial and transportation branches, in which they play a crucial role. For some applications, such as compressing ethylene to pressures over 300 MPa to produce low-density polyethylene or compressing gases with very low suction temperatures (as low as –150°C), these compressors are indispensable [16–18]. It follows that they are customarily considered to be the heart of an installation, as their high reliability is truly the *sine qua non* - in terms of safety and the availability of the entire plant. An industrial investigation conducted, clearly identified compressor valves to be the main cause of unscheduled compressor shutdowns, resulting in costly downtimes [19–20]. Furthermore, the investigation stated that among the most common causes of valve failure were high-impact velocities, wear, or application conditions. It stands to reason that proper care in valve design is not only desired, but it is decidedly obligatory [21–22]. Nowadays, reciprocating compressors are mainly fitted with automatic valves, which are actuated by the pressure difference in front of and behind the valve.

MATERIALS AND METHODS

Materials

The evaluation of reciprocating compressor component failure requires a systematic execution to achieve better results. The stepwise procedure includes:

i. study of the system and components of compressors;
ii. identification of the system and components of compressors;
iii. collection of data for the maintenance of compressors;
iv. processing of data.

The compilation of failure data stands for the foundation of any reliability and maintainability simulation or process. Whether it is made through testing or maintenance feedback and observed field operation, the study of individual component failure provides data on failure rate and all other reliability parameters. This data can be used as input for reliability and maintainability simulation.

To carry out the case study, it is necessary to have data available for analysis. The data that will be used in this case study are obtained from several sources in Powergas Global Investments (Nigeria) Limited (PGIL), such as the operations and maintenance registration system in use, the daily hours files, and some maintenance reports available in the company. The events that are considered failures are those resulting in the unavailability of the machine. The reciprocating compressor components data collected is shown in Table 1, which shows the summary of the data collected.

The period analyzed is from January 2016 to January 2020. To limit the study, it was taking only into account those failures that the details were properly identified, namely in aspects where it was possible to know exactly the time of failure and the time of repair or downtime of the machine caused by the failure.

Data Collection of Compressor Component Failures

As already seen, the case study focuses on the failures of gas reciprocating compressors, the product of Atlas Copco compressors at PGIL. Therefore, data collection was done for a time window between January 2016 to January 2021. The survey was done in such a way that, for all the failures collected, it was possible to associate each failure with the respective system in the reciprocating compressor package considered in this study, the day the failure happened, the operating time until the failure of the system/component, as well as how long the compressor (machine) has been down due to component or system failure. In the historical summary of failures of reciprocating compressor components, it is important to note here the following aspects.

i. *The time to failure (TTF):* This refers to the system or a component (if the failed component is identified), that is, the time in which a system/component leads to failure since the reference date January 2016 (or since the date that machine is placed into operation after the last failure). For this case study, it was not the amount of time that the compressors (machines) were not running but able to operate, due to production issues, for example, for this reason, the mean time to failure (MTTF) is then equal to the mean-up-time.
ii. *Down-time failures:* In this case, it refers to the total time the compressor was down (unavailable) because of the failure associated with a certain component.
iii. *The mean time to repair (MTTR):* This is defined as the average time it takes to repair a system (usually technical). It was considered as the actual maintenance or restoration time of the failed component.

Source of Data

The data for this dissertation work was obtained from the Powergas Global Investment Nigeria plant at Ogbele, Ahoada, Rivers State.

Powergas operations are predominantly in Nigeria. Powergas operates four (4) CNG plants across Nigeria with a total production capacity of over 720,000 SCM per day. Powergas is planning its fifth CNG plant which will add 384,000 SCM per day capacity. With offices in London and Lagos, Powergas is also escalating its innovative "Gas on Wheels" CNG solution to other African nations, specifically South Africa, Ghana, Tanzania, Mozambique, and Angola.

Powergas was instituted to address the severe electricity and energy challenges in Nigeria. Plagued with an inadequate gas pipeline infrastructure, unreliable grid-connected power, and expensive, environmentally polluting diesel standby power generation, Powergas' competitive and clean "virtual pipeline" offering is a "win-win" for the Nigerian market.

Powergasbuys NG from reliable downstream gas producers, such as Shell NG, with strict gas composition quality requirements. Then, the gas is further cleaned and processed, removing condensates and moisture content. The already-treated gas is then compressed and filled into the specialized high-pressure gas skids for delivery.

Table 1. Compressor component failures analysis for five years.

S. N.	Name of Components	Year 1 (2016)	Year 2 (2017)	Year 3 (2018)	Year 4 (2019)	Year 5 (2020)	Total Number of Failures in Four Years
1.	Valves.	10	6	7	5	5	33
2.	Seal.	8	6	6	5	4	29
3.	Pistons.	2	2	2	1	1	8
4.	Bearing.	7	5	3	4	3	22
5.	"O" rings.	9	7	7	5	4	23
6.	Cylinders.	4	2	3	2	1	12
7.	*Total*	40	28	28	22	18	136

Table 2. Total failures of the components occurred in four compressors.

S. N.	Years	Frequency (n)	Total Downtime (hours) (Σt)	Mean Downtime (hours) $(1/n\Sigma t)$
1.	Year 1.	40	4209.87	105.25
2.	Year 2.	28	3355.16	119.83
3.	Year 3.	28	14622.34	522.23
4.	Year 4.	22	13358.37	607.20
5.	Year 5.	18	5582.65	310.15
	Total	136	41128.39	1664.65

Failure Modes and Effects Analysis (FMEA)

This is a technique for identifying failures and the failures' consequences within systems or components. When this is done together with a critical analysis the combined method is then FMECA.

That is, to provide data on:

i. Failure rates of the system, possible failure modes, Mean Down Time (MDT) and
ii. MTTR, which is expressed as:

$$MTTF = \frac{Total\ hours\ of\ maintenance}{Total\ number\ of\ repairs}, \tag{1}$$

$$MTTR = \frac{1}{\mu}. \quad (2)$$

iii. Mean Time Between Failures (MTBFs), operational maintenance, hazards, and their consequences, etc. But before the reliability and maintainability analysis at the system level, input in the known component failure data must be provided. MTBFs is expressed as:

iv.

$$MTBF = \frac{Total\ hours\ of\ operation}{Total\ number\ of\ failures} \quad (3)$$

MTBF = T/R, (4)

where T is the total failure time and R is the number of failures.

$$MTBF = MTTF + MTTR \quad (5)$$

There are many methods in evaluation by reliability analysis, but special attention shall be given to the reliability and maintainability data compilation (component level), because this is the method that is directly associated with the principal goals of this study.

The Failure Rates

The failure rate (usually denoted by the Greek letter λ) is a very valuable quantity. This is defined as the probability of a component failing in one (small) unit of time.

The formula for failure rate is given for repairable and non-repairable systems, respectively as follows:

$$Failure\ rate\ (\lambda) = \frac{1}{MTBF} \quad (8)$$

or

$$Failure\ rate\ (\lambda) = \frac{1}{MTTF}, \quad (9)$$

where MTBF is the Mean Time Before Failure and MTTF.

Failure rate can be defined as rates for specific components, and for complex products like cars or washing machines. In the latter case, we need to be clear about what is meant by a failure.

RESULTS AND DISCUSSION

Compressor Failure Data Collection

This research work focuses on the gas reciprocating compressors at PGIL. The reciprocating compressors are the most common machines installed in the company to compress the gas coming from the gas supply source. Gas compression devices are always part of a more or less complex system where a failure of the system can lead to severe consequences. The objective is therefore to perform an evaluation, of the failure rate, reliability, and maintainability of the gas reciprocating compressor components. This work (case study) was carried out with the personnel from the maintenance and operations department of PGIL.

From the analysis of the available information, it was verified that, over the time frame considered, some of the systems creating the compressor were affected by some failures, some with some considerable frequency and others not so. The compressor component failure analysis for five years (from the year 2016 to 2020) is shown the Table 3.1 while the number of failures (n), the total downtime (Σt), and the mean downtime (MDT) $(1/n\Sigma t)$ are displayed in Table 2.

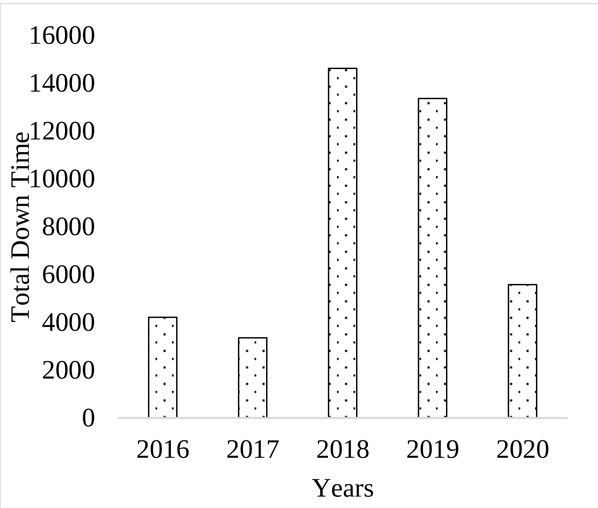
The failure times of four gas reciprocating compressors used in PGIL in the period of five years are shown in Tables 1 and 3.

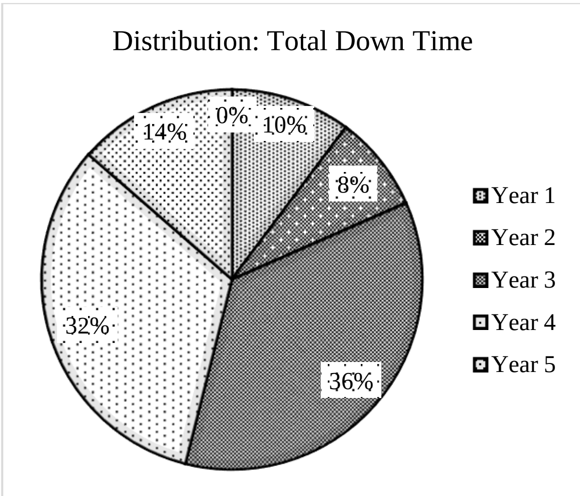
Graphical Representation

The graphical representation allows better visualization of the priority analysis of components that have suffered failures. Therefore, from the values obtained in Table 1, the graphical representations were created in order of the total downtime (Σt), the number of random failures (n), and the mean downtime ($1/n\Sigma t$), to obtain indications about the systems causing more unavailability (downtime) and the systems which are less reliable (number of failures).

Graphical Representation in Order of the Total Downtime (Σt) of Compressor Components in Five Years

This analysis allowed us to identify the year that most penalized the availability of the compressors, that is, the year that was responsible for the longest time of immobilization of the machine (gas compressor). The graphical representation of Figure 1 shows that the year 2018 was the most penalized year of the compressor during the period under analysis. This penalty totaled a downtime of 14622.34 hours. Figure 1(a) shows a graphical representation of the total downtime of the five (5) compressors within four (4) years, in which the year 2018 recorded the highest total downtime, and Figure 1(b) shows the total downtime distribution percentage (%) with year 3 (2018) recorded the highest percentage, that is, 36%





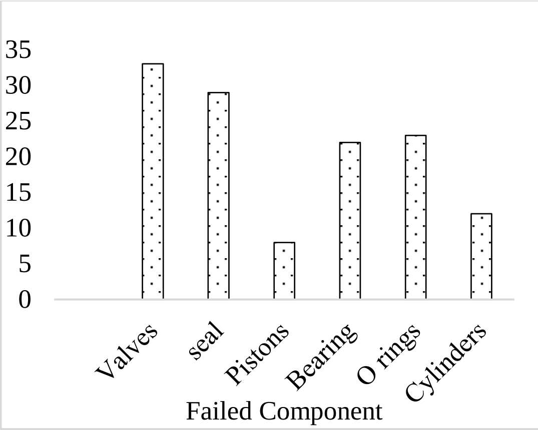
(a) Total downtime. (b) Total downtime distribution.

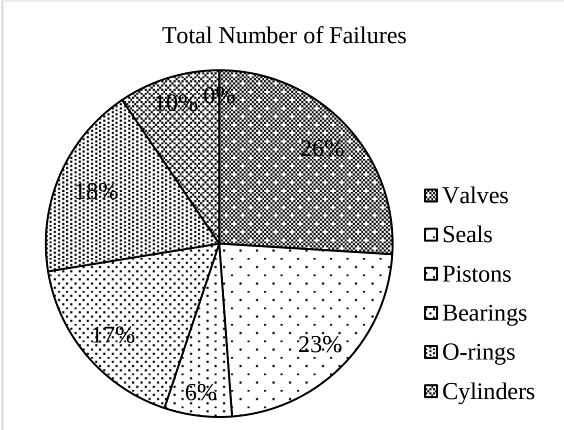
Figure 1. (a) & (b) Graphical representation: total downtime.

Graphical Representation of the Number of Failures (n)

The number of compressor component failures analyzed, from Figure 2, shows that the number of failures recorded indicates that valves had the greatest number of failures occurred, which is 33 malfunctions, whereas Figure 2(a) shows the representation of the total number of failures that occurred in compressor components in the period 4 years and Figure 2(b) show the compressor components failures distributions in percentage (%), and the components that recorded the highest percentage was valves with 26% of total failures.

International Journal Thermodynamics and Chemical Kinetics
Volume 10, Issue 2
ISSN: 2456-6977



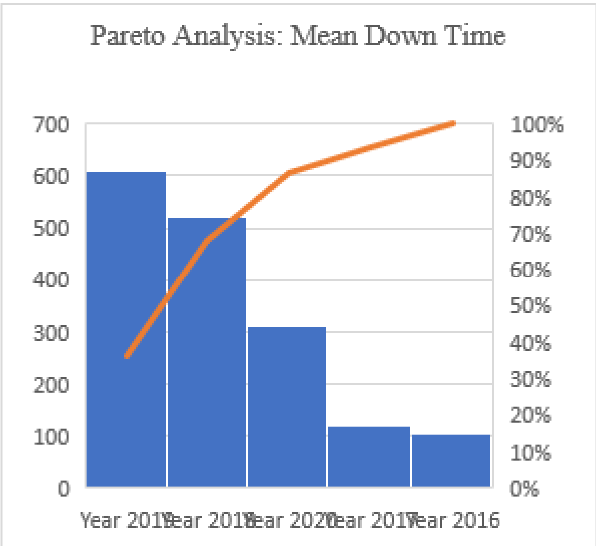


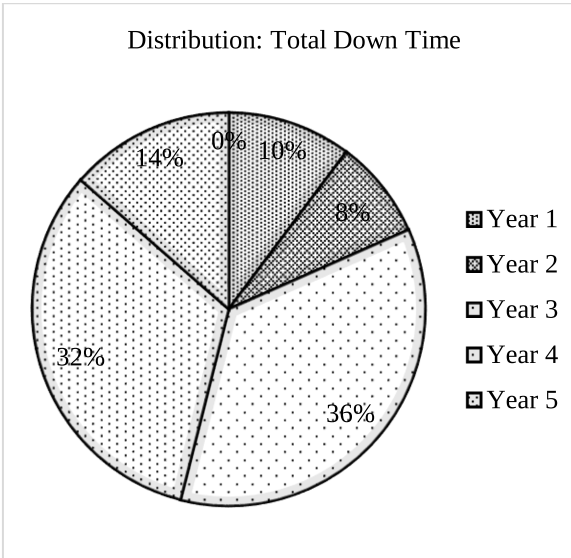
(a) Number of failures per component. (b) Percentage total number of failures.

Figure 2. (a) & (b) Graphical representation (number of failures per component).

Pareto Analysis in Orders of the MDT ($1/n\Sigma t$)

The analysis from Appendix G shows the staggering systems according to mean downtime (in fact, the mean time the compressor was down due to the total failures associated with a certain component per year). From Figure 3, analysis indicates that the year 2017, was the year that had the higher mean downtime of 51.4 hours with 30%, as can be seen in Figures 3(a) and (b).





(a) MDT graph. (b) MDT distributions.

Figure 3. (a) & (b) Pareto analysis (MDT).

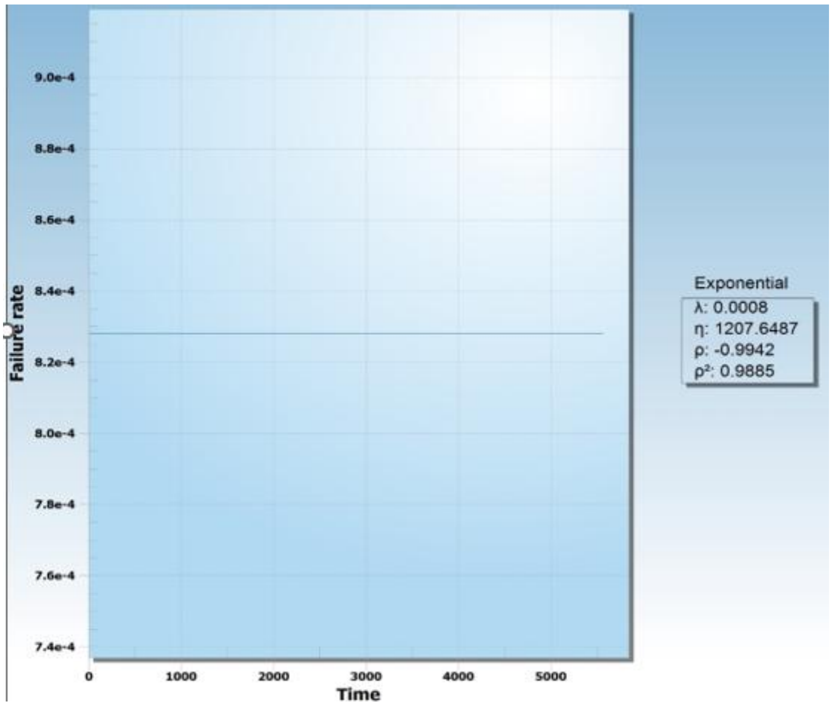


Figure 4. Failure rate plot for compressors in 2017.

In Figure 4, the value of parameter λ= 0.0008 indicates that the failure rate of the compressors is constant. It however justifies the fact that exponential probability distribution is a failure distribution that has a constant failure rate.

Causes of Valve Failure

Environmental Causes of Valve Failure

Reciprocating compressor valve failure is sometimes rooted in problems that originate from environmental factors. The following factors are among the most common environmental causes of valve failure:

i. corrosive contaminants;
ii. foreign material;
iii. liquid slugs; and
iv. improper lubrication (stale lubricant or valve failure due to over lubrication).

Mechanical Causes of Valve Failure

Compressor valve failure can also be the result of mechanical factors, some of which may develop internally unbeknownst to the operator and others which are due to user negligence. If a valve experiences excessive levels of stress due to system overheating or overload, the valve could easily wear down and lose its ability to function as projected. If a gas compressor is used in a way that goes against the advice of the producer, this too could lead to valve failure. The following factors are among the more common mechanical causes of valve failure:

i. high-cycle fatigue;
ii. off-design operation;
iii. impact stresses;
iv. spring failure; and
v. pulsations.

Preventing Valve Failure

Ensure proper maintenance conduct, to prevent the failure of a gas reciprocating compressor valve, conduct proper maintenance. Monitor the valve and corresponding system components on a periodic basis. The charts and stats can give you concrete information as to whether the system is behaving as it should. Also, check the temperature of the system and listen for unfamiliar sounds as these can serve as key indicators to the root of the problem.

Piston

Piston is a component of reciprocating compressors (engines or pumps). The method of operation of the compressor greatly relies on the piston. This is because the piston is the component that compresses the gas. The piston must have strength, weight, and be compatible with the gas to be compressed.

It also moves the energy from the crankcase to the gas contained in the cylinder in order to prevent the refrigerant from leaking through the gap. The piston figure is shown in Figure (e) in Appendix H.

In between the piston and cylinder walls, this component is usually covered with piston rings. The piston failures modes and the causes failure with remedies are shown in Appendix J.

Bearings

Bearings are machine element that constrains relative motion to the desired motion and reduce friction between moving parts. They give support to the shaft rotation inside the compressor (machinery). Bearings are not the least component given that they can be found throughout the compressor's frame. The failure modes and the causes of failure with remedies of the bearing are shown in Appendix K.

They ensure that other components in the compressor are properly positioned axially and radially. An instance is that of the main bearings which are fixed in the frame to ensure that the crankshaft is well fitted. The figure for the bearing is shown in figure (h) in Appendix H.

"O"-Rings

"O"-rings are probably the most common elastomeric sealing device. They are devices that comprise of a circular cross-section that is formed or melded in the shape of a ring or toroid. This is shown in figure (b) in Appendix H.

Some of the "O"-rings' failure modes are:

a. rapid gas decompression;
b. abrasion;
c. installation damage;
d. fluid incompatibility, etc.

"O"-ring failure modes and the causes of failure with preventions/corrections are shown in Appendix L.

Seals

Seal is a device that helps join systems or mechanisms together in order to prevent leakage (e.g. in a pumping system), containing pressure, or excluding contamination. The effectiveness of a seal is dependent on adhesion in the case of compression and sealants in the case of gaskets. The figure of the seal is shown in figure (i) in Appendix H.

Some of the failure modes and how to avoid them are stated below.

Lack of Adequate Fuel Gas Pressure During Start-Up

As a result of insufficient pressure of the buffer gas during start-up can cause the process gas inside the compressor to go through dry seal faces. The seal of the gas compressor's groove is ineffective causing damage to the seal's surface if it's exposed to dirty gases.

Some preventive measures are:

i. introduction of start-up interlock;
ii. ensure of excess availability of gas in the system before start-up.

Failure of Oil Traps on the Barrier Seal

The oil traps are provided in the drain of the buffer gas line to trap and drain the oil that could come into the barrier seal zone. The failure of the trap will alter the pressure in the barrier seal zone. This leads to the ineffectiveness of the barrier seals. The seals can eventually fail, if foil is present in the barrier seal for an elongated period of time.

Preventives measures are:

i. the functionality of the oil traps should be checked periodically;
ii. ensure to check the functionality of the oil traps, if the PCV upstream of the barrier seals are not able to maintain the pressure on the barrier seals.

Open Rupture Disc on the Bypass of the Primary Vent PDI

Opening of the rupture disc will indicate a lower reading of the PDI on the primary vent.

Lower PDI

Seal failure may possibly indicate when PDI readings lower. Misleading information may lead operators to unnecessarily change the seals.

Some preventive measures are:

i. Ensure to check the trends of the PDI on the valve on the primary vent.
ii. The flow meter reading should be checked on the primary vent.
iii. Ensure to investigate when the problem arises (maybe after any seal replacement or any trip event).
iv. The temperature just downstream of the rupture disc should be measured.

CONCLUSIONS

The research work was carried out in the company with the cooperation of the leaders, mostly the personnel who were working directly with the reciprocating compressors with a mission of continuous quality improvement. This research work was possible, based on the failure history of reciprocating gas compressors that was recorded by the operations and maintenance team of the company and able to:

i. Identify the critical components of reciprocating gas compressors.
ii. Examine the main causes of failures in the reciprocating gas compressors and provision of possible solution to some of the failures.
iii. Also, propose actions to improve the reliability, availability, and maintainability of the compressors.

From results analysis within the period of five years, it was observed that the third year (year 3) had the highest hours of downtime of 14622.34 hours, which implied 36% and the lowest downtime of the years was the year 2017 (year 2) with the total downtime of 3355.16 hours, which implied 8%. It was also observed that out of 136 numbers of compressor component failures times within the period of five years, valves recorded the highest number of failures 33 numbers of times, implying 26%, while piston had the lowest number of failures with 8 failures, that is, 6% of the total failures within the period of five years.

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