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Analysis of Set of Valve from Hermetic Reciprocating Compressors Under Accelerated Life Test (ALT) by Alternative Machine in Replacement of the Usual Compressor Bench Test

Jairo Aparecido Martins  
*Barnes Precision Valve*

Daniel L. Leite  
*Barnes Precision Valve*

Luiz G. Martins  
*Barnes Precision Valve*

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ABSTRACT

In search of plenty understanding and continuous improvements of hermetic reciprocating compressors several analysis methods have been applied. Among them finite element methods (2D and 3D) and laboratorial experiments are the most common and useful to validate the compressor design, some of them particularly applied to the valve design; which is of such importance to the compressor effectiveness. An alternative endurance test machine in replacement to the reciprocating compressor is presented to test a set of valve plus the valve plate under accelerated life test (ALT). Only one particular set of valve model (valve plus valve plate) was tested; which undergo several speeds/loads at the same pressure level under controlled humidity. The results obtained from the valve set were plotted on a graph that reveals the endurance versus the machine speed/load change, those curves represent the valve Weibull ALT lifetime. The values were analyzed using the normality and the probability approaches beyond of t-student to determine the difference among the lifetime values towards the p-value. Beyond of the Weibull graph, microscopic analysis of fractured surface of the valve and on the valve plate seat using SEM/EDS was done to have a better phenomena characterization based on the damage and fracture micromechanics. Based on the Weibull curve and microscopy analysis gotten the flapper valve set, the performance of this assembling is known. Those results confirm the machine reliability and give the valve endurance lifetime under impact test.

1. INTRODUCTION

In the study of the flapper valve design Kerpiççi [1] has shown the importance of the valve design and the mass flow dependency of the valve area and pressure; which results on different mass flow depending on the valve design. The same author reveals the change in the mass flow velocity along the valve shape surrounding. For instance, the most severe stresses on the suction valve during opening occur at the operating conditions and region that produces the maximum mass flow rate, Figure 1. Even with the small pressure difference, small water condensation might be expected at those regions [1]. Moreover, according to Laughman [7] the presence of liquid refrigerant in the compressor cylinder during operation or liquid slugging, is one of the most common causes of failure in reciprocating compressors. Under normal operating conditions, the refrigerant exiting the evaporator is 100% vapor, so that no liquid is present in the stream entering the compressor. Unfortunately, liquid refrigerant may accumulate at the suction port of the compressor for a variety of reasons [7]. These appointments make the gas and test environmental control of such importance when experimental tests are performed. Because of the large time required to test a valve in a compressor for life expectancy, the idea of an accelerated life test is a very attractive one [2]. The valves undergo highest stresses what means more severe conditions than is seem at normal operating conditions but on the other hand can indirectly represent its usage into the reciprocating compressor [3]. This paper aims to demonstrate the machine reliability as well as the endurance on the set of valve plate plus the flapper valve under the accelerated life test (ALT) [6], in order to supply to designers important characteristics that should be taken into account when designing the set of the valve. Beyond of this the alternative machine presented opens the possibility of having a cheaper, faster and direct test to design precisely the set of valve. According to Cunha, E. and Pavanelo [4] some experimental analysis are of such importance experimentally, like working diagram (Pressure versus Volume), dynamics (flow force, stiffness) geometric design (valve and valve plate), and stresses (bending stress and impact stress).
These characteristics are totally present on the valve design but are far easy to be simulated or even experimentally determined. According to Kim et al. [5] the thickness of valve was the most sensitivity part to the all responses such as stress, volume and deflection.

The computational simulations have given important inputs to the experimental bench tests once the tests conditions can be better understandable and also basis to the failure analysis. On the other hand some failure modes are identified by experimental ways from field failures, like those verified by Woo S. and O’Neal D.L [6] where in order to have a more robust product some design changes were proceed with. Changes like; trepan redesign on the valve plate due to a sharp edge found in field failure, the width size of the same trepan increased, the valve material changed from Carbon to Stainless and moreover other processes like tumbling to the valve and ball peening and brushing process were added. This problem solving approach reinforces the experimental test importance.

2 – MATERIALS AND METHODS

2.1 – Endurance Test Machine

The machine used to perform the tests is a mechanical machine that uses an electrical motor (AC) to rotate a drilled table (air shuttle) that supplies the fluid to the valve lifting. The frequency is adjusted manually by the motor speed setting and the pressure by a valve (pressure gage) introduced in the main fluid line. The machine also has fluid under pressure reservoir (two air tanks in line) that can guarantee the steady mass flow through the nozzle. The frequency is measured by an inductive sensor that gets the signal from the drilled table.

The machine has a valve plus valve plate holder slightly over the drilled table rigid positioned to guarantee the perfect stability when the air pass through the set of valves. Another important test parameter is the humidity control, done by dryer model Desidrat 2 and filter drier model DML 303 Danfoss along the pressure line. The failures were monitored and thus even a small crack, human visually detected, is considered as being a fracture event. The tests were performed using a commercial valve plate (sintered) and valve design made in high carbon steel, which passed through all the process steps usually applied on the high performance valve manufacturing technology. The fractured valves were analyzed afterwards by SEM/EDS (Figure 9).
Figure 2 – Picture of the valve and valve plate used on the tests.

The tests were done using the same process parameter for each set of valves, being the valve plate kept the same. Each test gets the average valve lifetime from those valves and the samples quantity indeed determined based on t-student equation to a reliability of 78% [6].

\[ n = \left( 1.96 \cdot \frac{\sigma}{EM} \right)^2 \]  \hspace{1cm} (1)

Being; \( n \) the samples quantity, \( \sigma \) standard deviation and \( EM \) error margin.

Both valve and valve plate were analyzed afterwards to find out the failure micromechanics. The humidity was monitored in order to approximately represent the compressors hermetic condition. The tests parameters were; the frequency (s⁻¹), pressure (atm) and the humidity (%). The pressure was controlled at 4 atm and the tests were performed at room temperature, see Table 1. The valve load was determined experimentally by the static spring rate curve building using an elasticometer Reichter NRE-D2, load precision 0.001N and height precision 0.010mm. The height of the valve was measured when the machine runs, using an altimeter with an electrical special sensor. Afterwards the frequency against valve height curve empirically determined (Figure 4). The humidity was monitored using a humidity meter Testo 615. The machine adjustment focused three types of stresses, bending stress due to the valve lifting, the impact stress on the valve plate and bending stress (overshoot), and later static bending [2]. Despite of the machine allows an upper stop and an additional nozzle to simulate additional localized impact and bending, these accessories were not applied on those tests. These accessories whether used would simulate some contact on the compressor piston.

Table 1 – Machine test parameters adjustments (pressure 4 atm, room temperature).

<table>
<thead>
<tr>
<th>Test #</th>
<th>Cycle [s⁻¹]</th>
<th>Humidity [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>216</td>
<td>54,0%</td>
</tr>
<tr>
<td>2</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>216</td>
<td>23,5%</td>
</tr>
<tr>
<td>6</td>
<td>200</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>183</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>187</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>180</td>
<td></td>
</tr>
</tbody>
</table>

In order to validate the results and the machine stability the test of Statistical Significance (equation 2 and 3) was done as well as the Normality Test (Shapiro-Wilk) to all the trials, as follow in the equation (4);

\[ t = \frac{\bar{y}_1 - \bar{y}_2}{\sigma \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \]  \hspace{1cm} (2)
where \( \tilde{y} \) = average of the data, \( \sigma \) the standard deviation and \( n \) the samples quantity.

Normality test (Shapiro Wilk)

\[
W = \left( \frac{\sum A_i X_i}{\sum (X_i - \bar{X})^2} \right)^2
\]

where and \( A_i \) is a weighting factor.

4- RESULTS

4.1- Valve characteristics

The variation of the valve height against the frequency, determined experimentally, presents a non-linear curve. The valve height increase is more pronounced at low frequency values up to 95 s\(^{-1}\), based on the first half derivative (angle), while at higher frequencies a slightly valve height increase is found. This behavior shows up a non-linear load variation with the air pressure on the valve, as verified on the Figure 3 and equation (5).

![Figure 3 – Variation of valve lifting height versus frequency.](image)

The logarithmic trend of the curves suggests an empirical equation. The values of the constants \( k \) and \( a \) were determined by fitting the curves by the least-squares method. The high values of the x2 obtained (0.9565) indicate a good fit.

\[
y = 2.4036 \ln(x) - 2.7368 \quad (5)
\]

- being \( y \) the height (mm) and \( x \) the test frequency (s\(^{-1}\)).
When statically analyzed the valve presents a linear behavior different of the dynamical test, Figure 5

![Figure 4 – Valve “spring rate” graph](image)

This linear behavior is commonly used to describe the spring’s load versus deflection. The valve value of the constant k was determined by fitting the curves by the least-squares method. The high values of the x2 obtained (0.9924) indicates a very good fit.

\[ F (N) = 0.0011 \times x \text{ (N.mm)} \]

- F is the force in Newton, the 0.0011 is the spring constant and the x is the valve height deflection in millimeters under load when assembled under the valve plate.

4.2- Endurance (statistical)

4.2.1- First trial (No humidity control)

The first test trial was done without humidity control, as showed in the Table 1 (test # 1-4). The results were very discrepant along the test once the failure sometimes was anticipated (theoretically) to lower cycles (loads), fact that make the test running suspicious (Figure 5). Once having suspicious tests they were stopped and the failure analysis proceeded with. The curve had an inflection to a lower stress level, specifically at 167s-1; which makes the test unreliable. This kind of behavior is not usually found except when a stress raiser is present, fact that was verified and is shown in the item 4.3.
4.2.2- Second trial (controlled humidity)

The Weibull chart (Figure 6) shows the curves of the test conditions within Test # 5-9. It can be seen that the higher number of cycles, which represent a higher load level, presents shorter lifetime and are pretty close at the 90B10 Weibull analysis, while low cycle promotes an extended lifetime. Low cycles are more a part from the equality, as demonstrated by the p-value analysis afterwards.
Table 2 compares the test# against the p-value for each interaction. The p-value limit to consider the tests different is \( \leq 0.05 \). As can be seen the tests numbers 5-7, 5-8, 6-7, 6-8 and 7-8 cannot be, with a probability of 95%, considered the same, on the other hand the comparison between test # 5 and 6 cannot be considered, with the same probability, different.

Table 2 – P-value of different test #

<table>
<thead>
<tr>
<th>Test #</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>Two sample T-Test</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>-</td>
<td>0.484</td>
<td>0.001</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>0.484</td>
<td>-</td>
<td>0.017</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>0.001</td>
<td>0.017</td>
<td>-</td>
<td>0.000</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>0.000</td>
<td>0.000</td>
<td>0.000</td>
<td>-</td>
<td></td>
</tr>
</tbody>
</table>

- Test #5 = 216s\(^{-1}\), test #6 = 200s\(^{-1}\), test #7 = 183s\(^{-1}\) and 167s\(^{-1}\)

The upper limit tests #4 and #5; which are the highest values can not be distinguished statistically. The cycles are pretty close what makes the loads similar.

4.3- Microscopy and Failure analysis (First trial without humidity control)

The first trial failures happened when performed without humidity control; which revealed damages on the valve plate along the experiments, Figure 7. The non-logical values gotten at the tests beginning reveal that something strange happened with the valve owing the discrepancy of the results got with table spinning speed change (load). The two regions broken at the valve (Figure 7a), matches with the damaged regions at the valve plate (Figure 7b). The Figure 8 (a) reveals the usual fractured surface found on this type of material, dimples fracture micromechanics reinforces by EDS analyses the corrosion previous hypothesis and it generates the need to control the machine environmental, Figures 8(b) and 9.
Figure 7 – (a) overview of the fractured valve, (b) damaged valve plate surface

Figure 8 – (a) expected fractured surface at the valve plate sintered material, (b) area with corrosion on the valve plate

Figure 9 – Electronic Dispersive Scanning of the corrosion suspected region
The corrosion really does exist based on the Electronic Dispersive Scanning analysis due to the high Oxigen together with the iron (Fe) present in the steel localized presence and it suggests that the humidity on the line is the main responsible to the accumulated damage.

4.3- Microscopy and Failure analysis (Second trial with humidity control)

Once the humidity control was considered as being an important factor the tests were reinitiated, and thus the results shown on the Figure 6. The analysis on the microscope after the test trials reveals that once humidity is under control the valve plate does not present the corrosion verified on the first trial. Therefore the tests results are more consistent with the expected endurance tests results.

Therefore the analysis now is focused on the valve instead of the valve plate. The Figure 10 shows that all the failure surfaces have the same morphology, differing just on the length of the divisor line close to the middle thickness section. The difference is owing the change of the stress, which is directly related with

![Figure 10 – Morphology of the fractured valves under tests. (a) Length 429microns, (b) Length 940microns.](image)

Figure 11- Fatigue striations

The phenomenon of the fracture is characterized by fatigue since there are striations as revealed in Figure 11. The final fracture is not found because the stress despite of resulting low lifetime does not generate significant final fracture zones. This morphology characterizes the fracture as being reversed bending, mild stress concentration from low nominal stress.

![Figure 11- Fatigue striations](image)
5 - CONCLUSIONS

Based on the experiments and the data collected the following conclusions can state:

1- The valve presents a linear behavior usually called “spring rate” (load versus deflection)

2- The valve height against cycle is a non-linear curve (logarithmic) basically due to the pressure drop. It is believed that it is owe the unstable pressure (pressure loss) at low cycles.

3- The humidity in the testing line and environmental damages the valve plate due to corrosion; which produces a crater with the impact, jeopardize the valve endurance.

4- The results gotten from the valves tested in the machine are normal and the change on the machine load (spinning speed) is easily identified, what reveals the machine stability.

5- The crater presence creates a stress raiser that makes the valve failure. The failures are found exactly at the regions where the craters are present.

6- The striations presence reveals that all the failures had the fatigue phenomena as the root cause.
   The morphology of the failed surface is characteristic as being reversed bending, mild stress concentration from low nominal stress.

7- Once the tests planned, those are reliable, simple and cheaper to be proceed with, which make the alternative testing method very attractive in replacement of the usual reciprocating compressor bench tests.

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