Reliability Improvement for Booster Reciprocating Compressor in CCR Reformer

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In charge of this case study for reciprocating compressor for six years. Present a lesson learned based on hands on experience.

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Presentation Overview

1. Abstract
2. Problem Overview
3. Troubleshooting
4. Recommended Solutions and Results
5. Lessons Learned
1. Abstract

CCR(Continuous Catalyst Regeneration) Reformer process inherently creates viscous liquid called green oil*. When reciprocating compressor are selected as booster compressor for process, green oil creation and carry-over must be taken into consideration.

This case study includes root cause analysis & its countermeasures in various aspects of process, mechanical design, condition monitoring system. It is based on actual experience to improve the reliability of the compressor in CCR Reformer.

* green oil formation
- green oil is formed by oligomerization or polymerization of light olefins and is catalyzed by acidic conditions(FeCl₂+HCl).
- green oil forms easily at high pressure and temperature.
Installed in 2005, the booster compressors in CCR Reformer process **transfer** rich hydrogen (H2) gas from reactor to H2 plant.

### Compressor System & Specifications

- **Number of Compressor**: 3ea
- **Number of Stage / Cylinder**: 3 stage / 4 cylinder (= number of piston)
- **Speed (rpm)**: 400
- **Suction Pressure (kg/cm²g)**
  - 1ˢᵗ stage: 2.1
  - 2ⁿᵈ stage: 5.7
  - 3ʳᵈ stage: 14.0
- **Discharge Pressure (kg/cm²g)**
  - 1ˢᵗ stage: 6.1
  - 2ⁿᵈ stage: 14.5
  - 3ʳᵈ stage: 33.6
- **Flow**: 41,933Nm³/h (= 33.77mmscfd)
- **Motor Power**: 5,000kw (= 6,702Hp)

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![Diagram of Compressor System](image-url)
2. Problem Overview

Since process revamp in 2009, all three compressors have run without stand-by and the number of compressor troubles increased drastically.
Most problems or issues involved damaged valves and cracked pistons.

2. Problem Overview

2009~2016 Damaged Parts

- Cracked Piston: 13%
- Piston ring: 9%
- Rider ring: 3%
- Piston rod: 4%
- Etc (crosshead, connecting rod etc...): 21%
- Valve failure: 50%

- Damaged valves
- Cracked Pistons
- green oil in valves
- Connecting rod bending
- Cracked Piston rod
To find the possible cause of the problem, every aspect in the process was reviewed as well as the mechanical design and integrity.

### Problem
- Valve Failure
- Cracked Piston

### Possible Cause

<table>
<thead>
<tr>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Increased generation of green oil after revamp.</td>
</tr>
<tr>
<td>▪ Main cause, but CCR reformer process inherently creates green oil.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ Ring type is not strong enough to endure foreign substance (green oil).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical Design and Integrity</th>
</tr>
</thead>
<tbody>
<tr>
<td>▪ For piston to float (Free Floating Piston), it is made of a light (low density) material but its mechanical strength is low. Due to green oil, pistons could not endure additional stress (larger than design).</td>
</tr>
</tbody>
</table>
Since process revamp in 2009, Booster Compressor’s operating condition changed little, though well within operating range. Pressure ratios did not change much; however, discharge temperatures were higher than normal, yet below alarm set point T (145 °C=293 F).

<table>
<thead>
<tr>
<th></th>
<th>Before revamp</th>
<th>After Revamp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor at operating</td>
<td>2 run out of 3</td>
<td>3 run out of 3</td>
</tr>
<tr>
<td>Total Load</td>
<td>80,983 Nm3/h mmscfd</td>
<td>102,648</td>
</tr>
<tr>
<td></td>
<td>65.21</td>
<td>82.66</td>
</tr>
<tr>
<td>Pressure Ratio 1st/2nd/3rd Stage</td>
<td>2.20/2.39/2.31</td>
<td>2.24/2.41/2.32</td>
</tr>
<tr>
<td>Discharge Temperature 1st/2nd/3rd Stage</td>
<td>105/101/106 °C</td>
<td>112/106/113</td>
</tr>
<tr>
<td></td>
<td>221/213.8/222.8 F</td>
<td>233.6/222.8/235.4</td>
</tr>
</tbody>
</table>
3. Troubleshooting

Changed the operating condition, the rust (Fe2O3) and Cl2 dust increased green oil.

< Possible Cause of green oil forming >

- **Increasing light olefin**
  Decreasing H2/HC Ratio increases light olefins.

- **Increasing seeds of green oil like Rust and Cl2 dust**
  - Rust(Fe2O3) generated in the pipe by exposure to the atmosphere during turnaround.
  - Cl2 dust is created during initial period of start-up and by using new catalyst.

<table>
<thead>
<tr>
<th>Before revamp</th>
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</tr>
</thead>
<tbody>
<tr>
<td>H2/HC Ratio*</td>
<td>Low</td>
</tr>
<tr>
<td>green oil</td>
<td>green oil increased</td>
</tr>
</tbody>
</table>

* H2(Hydrogen)/HC(Hydro Carbon) Ratio in process gas composition.
At the initial design stage, a ring type discharge valve was used. **A ring type discharge valve** is not strong enough to endure foreign substances.

**<In case foreign substance carries-over discharge valve>**

- **Step1.** Sticking occurs due to foreign substance between valve sheet and ring.
- **Step2.** Late opening and differential pressure increase between A area and B area.
- **Step3.** Increase impact and tumbling between ring and guard. (because outer ring’s stiffness is lowest, outer ring breaks easily.)
In order to float the FFP (Free Floating Piston), it is made of lightweight material. However, the material strength is not large enough to withstand the large stress exerted by green oil (larger than design one).

### Characteristic of FFP

To prevent wear of rider ring, piston must float during operation. Discharge pressure jets on the bottom side between piston and liner.

### Expected Actual Strength

Because of increasing pressure due to green oil. Actual Stress is higher than design.

- Compression Max. Stress: 172 Mpa @ Design condition
- Expansion Max. Stress: 302 Mpa @ Design condition
- Piston Yield Strength (520~630 Mpa)

### Mechanical Design - Piston
4. Recommended Solutions and Results

To avoid further generation of green oil, during plant turn around, catalysts like Fe2O3 and Cl (chlorides) were completely purged from the piping system, from the knock out drum to the discharge line.
After turn around, to minimize forming green oil, the Reformer process reduced light Olefin. Further, to reduce Chloride(Cl), the operating condition was adjusted during the start-up period.
Replaced original valves with a Poppet type valve, which have high reliability in liquid carry-over and sticking.

### 4. Recommended Solutions and Results

**Ring Type**

- **Appearance**

  ![Ring Type Image]

- **The pros and cons**
  - Tight Sealing
  - High Efficiency
  - Weak to accumulation of foreign substance
  - Low strength of outer side ring
  - High price

**Poppet Type**

- **Appearance**

  ![Poppet Type Image]

- **The pros and cons**
  - Because of increasing passing area, friction loss is little higher.
  - Advantage of inventory control
  - Higher Stiffness
  - Strong against Sticking
Discharge Valve Type changed from ring type to Poppet type in March of 2010. The mean life time of valve increased from 2.1 months with ring type to over 11 months with Poppet type.
4. Recommended Solutions and Results

Improve the geometry of a piston to increase its mechanical strength. As the material and method of production changed, the strength increased ~48% above original and without weight change.

- **Improve the geometry**
  (Profile of rib and its thickness)

- Method of production **from casting to forging** (strength increased about 26%)
- **Improve the material** (increased about 18%)

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</thead>
<tbody>
<tr>
<td>Original Material (X3CrNiMo13-4)</td>
<td>520~630</td>
<td>650~810</td>
<td>18~24</td>
<td>16~24</td>
<td>80 (50)</td>
</tr>
<tr>
<td>Improvement Material (X4CrNiMo16-5-1)</td>
<td>550~810</td>
<td>760~960</td>
<td>16~22</td>
<td>24~32</td>
<td>190 (70)</td>
</tr>
</tbody>
</table>
4. Recommended Solutions and Results

The original condition monitoring system could monitor only frame & crosshead vibration and simple process conditions (Suction & differential pressure, discharge temperature). Precision diagnosis could not be done due to the limited system.
4. Recommended Solutions and Results

Built in ad-hoc reciprocating compressor monitoring and diagnosis system. It included measuring and logic for installed cylinder pressure indicators, rod position and multi-key phasor. System can perform precision diagnosis through P-V diagram and monitoring vibration per each degree of crank angle.

- **Pressure-crank angle diagram**
- **Vibration per each degree of crank angle**
4. Recommended Solutions and Results

Number Of Maintenance Actions

- Total Maintenance
- Cracked Piston
- Valve Maintenance

- '06
- '07
- '08 Revamp
- '09
- '10
- '11
- '12 T/A
- '13
- '14
- '15
- '16
- '16 After T/A

- '10.3 Valve Type Change (Ring→Poppet)
- Sequentially change improved piston after revamp

Additional Actions

Result
5. Lessons Learned

In CCR Reformer process, as long as the process can accept it, it is important to select centrifugal compressors instead of reciprocating compressors during construction of the plant. If reciprocating compressors were selected, the following countermeasures should be taken into consideration.

a) Process

- To set up optimized operating condition to minimize liquid carry-over.
- To purge the piping system to reduce catalysis of green oil after turn around.
5. Lessons Learned

b) Mechanical Design

- If there are not any restrictions, cylinder lubrication type is recommended.
- If FFP (Free Floating Piston) is selected, strengthening of the piston should be performed.
- To select advanced valve type. (Poppet)

c) Condition Monitoring System.

- To consider monitoring and diagnosis system only for reciprocating compressor including inner pressure, rod position and monitoring vibration per each degree of crank angle.
Q & A
Thank you