ABSTRACT

The Turboexpander is an equipment that works under very critical conditions requiring very low allowable nozzle forces and moments. A solution to minimize the piping loads transmitted to the equipment is the use of expansion joints. A usual piping stress analysis normally is not enough to guarantee the turboexpander reliability.

This paper shows the results obtained in a movement test realized on metallic bellows expansion joints (EJ) used in a turboexpander piping system. The EJ were designed according to the expansion joints manufacturer association code (EJMA), the diameters range from 457 to 2,898 mm, the material of the bellows is Inconel 625 LCF and the shell materials are “killed” carbon steel, for refractory lined EJ or stainless steel 304H.

A special test device was developed to apply the design movements on the EJ at the factory. A digital dynamometer was used for data acquisition and the tests were performed on 16 expansion joints of two distinct types: hinged and gimbal. The EJ were pressurized with water during the test. The reactions and corresponding displacements for each step of the test were recorded during loading and unloading.

INTRODUCTION

Expansion joints (EJ) are commonly used in the petroleum industry. The Turboexpander, typical equipment in industrial plants, require the use of expansion joints in its system because of the lower allowable nozzle loads. There is a strong relation between the EJ correct function and the system reliability.

Therefore, it was necessary to develop an EJ movement test for use after complete construction of the expansion joint. With this test it is possible to anticipate EJ construction problems in time to mitigate an action.

This paper presents the results of a shop test which verifies the existence of internal construction interference, the friction between hardware components and obtains a comparison between the actual EJ behavior during the movement and the project values (behavior), according to EJMA standard (Expansion Joints Manufacturers Association) [1].

TURBOEXPANDER

The Turboexpander is the equipment responsible for the generation of electric energy produced from the hot gases regenerator effluent of the fluid catalytic cracking unit (FCC). These gases have operating temperatures ranging from 650 °C to 760 °C and internal pressures about 3.0 kgf/cm². With the intention to optimize the energy consumption within the refineries some new projects of turboexpander are in progress.

Due to service severity, the turboexpander piping system is, normally, of austenitic stainless steel 304H, material that presents high cost in its use, and requires, at least, wall thicknesses of 25 mm, to attempt the project requirements. Moreover, the piping layout shall attempt several prerequisites to guarantee the maximum efficiency and reliability of the turboexpander, since the equipment nozzles have tight stress limits.

In order to minimize the piping layout and to attempt those prerequisites, expansion joints must be used. During the turboexpander system basic project is determined the best route for the ducts connected to the turboexpander and are verified its flexibility. The loads transmitted to the machine nozzles are also verified as they cannot exceed the values established by the
Machine Code [2] or supplied limits. In Fig. 1, a schematically
drawing of a turboexpander ideal inlet duct arrangement can be
observed.

Fig. 1. Schematically drawn of a turboexpander inlet line ideal
lay-out [3].

**EXPANSION JOINTS**

An expansion joint (EJ) is a flexible device capable of
absorbing, with small reactions, the movements imposed in a
pressurized piping system [4]. Usually, pipes movements
originated from thermal expansion, equipment movement,
vibration and pressure pulsation. The restriction to these
movements generates stresses and reactions in the piping system
and its connections.

EJ are commonly used for the following [5]:

- Systems whose available space is insufficient to have a
  pipe route with adequate flexibility;
- Low responsibility Services (condensed, low pressure vapor, hot water, among others), when the EJ represent an
  economic alternative in comparison to a non-linear layout;
- Piping with large diameters (above of 20") or of
  expensive material, where there is an economic interest in a
  shorter runs;
- Piping where service requirements dictate linear and short
  runs;
- Piping that is subject to excessive vibrations, or linked to
  equipments where allowable stresses are very small.

The EJ are usually classified by the bellows material, which
"can be metallic, not-metallic (composite), elastomeric or in
PTFE [6]. The metallic EJ are used for work in high
temperature and pressure, non-metallic for low pressures and
high temperatures and elastomeric or PTFE for water systems
and some types of high pressure chemical products and
temperatures limited by bellows material. For the project
referred in this paper, the approach was metallic joints.

The main component of a metallic expansion joint is the
bellows, formed mechanically or hydraulically from a thin-
walled tube, contains only longitudinal welds. The bellows
exhibits significant flexibility, behaving like a spring which
deforms under low stress. It is manufactured from one or more
plies and composed of a single or multiple convolutions of a
suitable material. Special care should be taken in the material
selection for metallic bellows due to the modest thickness of the
metal which is subjected to high stresses and strains and
possible corrosion attack. Use of a more corrosion resistant,
stronger, or exotic material than specified pipe materials are
often required [7].

Moreover, for the appropriate bellows functioning, the
expansion joint is composed of structural components
(hardware), whose main functions are to support the proper
weight of the components, to resist the axial loads due the
internal pressure (pressure thrust), to limit undesirable
movements and to protect the bellows from overloads [6].

Four types of basic movements can be applied to the
bellows. Three of them are presented in Figure 2: axial, lateral
and angular. The fourth movement is torsion and must be
avoided; since the bellows exhibit unstable behavior under twist
torsion.
When it is compressed, the bellows resist the movement in the same way as a spring. The bellows spring constant depends on its geometry and the material’s properties.

The simpler expansion joint is the axial type that only consists of one bellows, used to absorb tension or compression movements. For absorbing the axial movements, they transmit through the system the loads of pressure thrust due to internal pressure that can be large. Thus, a high value of loads will be transmitted all the way to the equipment nozzles connected to the pipe system. Therefore, simple axial EJ are not commonly used in pipe systems connected to critical equipment.

Universal expansion joint is the EJ type when two bellows are used together. This configuration allow the system to absorb axial, lateral and angular movements, greater than in the axial type. As in the simple EJ axial type, the pressure thrust effect must be considered. To minimize this effect rigid rods are introduced which, however, restrict the axial movements.

A hinged expansion joints allows the rotation in only one plan, and because of the hardware they do not transmit pressure thrust force through the system. Hinged expansion joints are normally displaced in sets of two or three to better absorb the system movement.

Finally, gimbal expansion joint is capable of absorbing rotation in all planes and, as in the hinged type, it does not transmit pressure thrust force nor torsion to the pipe system. Thus, hinged or gimbal expansion joints are preferred to be utilized in a Turboexpander systems.

Figure 3 presents the types of EJ, just explained: (a) axial, (b) Tied universal, (c) hinged, (d) gimbal.

As the stress limits in the turboexpander nozzle are low metallic expansion joints are introduced in the pipe system layout. The hinged and/or gimbal type shall be used rather than the others. After the type of EJ are defined, additional criteria must be specified such as length, bellows material, expansion joint type and stiffness factors. The calculation of these coefficients is carried out on the basis of EJMA [2] criteria. The bellows convolutions amount and thickness as well as the number, height and pitch of its corrugations are estimated for the design project. This estimation will be the initial reference for the selection and scope of supply for the expansion joints project.

TEST DEVICE

A test mechanism was developed to realize the experiment in the hinged and gimbal expansion joints. The test consists of positioning the EJ on a support system on the vertical position; both ends closed by welded heads with a beam “I” welded to the top head extending past the center point by 2,000 mm to be used as a pivot arm (Fig.4), chains, pulley and a digital dynamometer to show the load value. The influence of the angle of the crowbar arm in the EJ reactions value was evaluated; however it did not have significant influence in the results.

The used dynamometer, Fig. 5 (a), have load capacity up to 10 tons. During the test, the given angle was verified with a device fastened to the EJ, shown on Fig. 5 (b). The application of the load was provided by a hand operator (Fig. 5 (c)).

The tests was carried out for 13 EJ, being 5 of the hinged type and 8 of the gimbal type. Table 1 lists each EJ by equipment number with corresponding pipe diameters and design characteristics.

The EJ will be installed in the turboexpander system of a Petrobras FCC unit, the EJ will be used in the inlet and outlet portions of the system. The tests were carried out moving each EJ until the design angle shown in the Table 1 was reached.
Fig. 4. Expansion joint in the test position (unit in mm). (a) Schematic draw of the test device and (b) Test device build of.

(a) (b) (c)

Fig. 5. Test Device. (a) Dynamometer used during the test, (b) angle measurement device and (c) Load application.

Table 1. EJ’s characteristics.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Movement</th>
<th>Design angle (˚)</th>
<th>ID (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Gimbal</td>
<td></td>
<td>1.7</td>
<td></td>
</tr>
<tr>
<td>16</td>
<td></td>
<td></td>
<td>6.2</td>
<td></td>
</tr>
<tr>
<td>17</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18</td>
<td>Hinged</td>
<td></td>
<td>4.6</td>
<td></td>
</tr>
<tr>
<td>19</td>
<td></td>
<td></td>
<td>7.9</td>
<td></td>
</tr>
<tr>
<td>20</td>
<td>Gimbal</td>
<td></td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td>22</td>
<td></td>
<td></td>
<td>1.0</td>
<td>2910</td>
</tr>
<tr>
<td>24</td>
<td>Hinged</td>
<td></td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td></td>
<td></td>
<td>1.4</td>
<td>1910</td>
</tr>
<tr>
<td>26</td>
<td></td>
<td></td>
<td>0.5</td>
<td></td>
</tr>
<tr>
<td>27</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>28</td>
<td>Gimbal</td>
<td></td>
<td>1.1</td>
<td>610</td>
</tr>
<tr>
<td>29</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The corresponding reactions of each step of the movement during the loading (increasing angle) and unloading process (decreasing angle) were registered.

Each loading and unloading test was carried through on three conditions of applied pressure: design, operating and no-pressure (atmospheric pressure). Water was used to pressurize the system. All the tests were carried out at ambient temperature. The design and operating pressures corresponds to each one of the EJ are presented in Table 2.

In the loading process, the pulley was set gradually in motion, and the EJ angular movement was from the neutral position. In the unloading process, the pulley was gradually set free so that the EJ could return to the neutral position because of the spring reaction (Fig. 6).

Figure 7 (a) and (b) shows one of the inspected EJ during the loading test. Observing the top of the EJ it is possible to see an angle from the EJ’s movement.

Table 2. EJ operating and design characteristics: temperature and pressure.

<table>
<thead>
<tr>
<th>Number</th>
<th>Temperature (˚C)</th>
<th>Pressure (kgf/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design</td>
<td>Operation</td>
</tr>
<tr>
<td>15</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>16</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>17</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>18</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>19</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>20</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>22</td>
<td>450</td>
<td>0.5</td>
</tr>
<tr>
<td>24</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>25</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>26</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>27</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>28</td>
<td>450</td>
<td>3.6</td>
</tr>
<tr>
<td>29</td>
<td>450</td>
<td>3.6</td>
</tr>
</tbody>
</table>
ANALYSIS OF THE TEST RESULTS

Figure 8, 9 and 10, presented on Annex A, shows the applied moments and the corresponding rotation movement for the design, operating and non-pressure cases respectively. The test was performed in steps of 0.5° up to design angle for each of the expansion joints. Using linear regression a tendency line was created and the corresponding equation is presented for each expansion joint.

![Diagram of loading and unloading](image)

Fig. 6. Loading and unloading schematic drawing.

For the tests under pressure the expansion joints required an initial load to initiate the movement.

Table 3 shows the results obtained in the movement test for expansion joint JE-22020 movement test. The bending moment is proportional to the increase in pressure.

<table>
<thead>
<tr>
<th>Test Pressure (kgf/cm²)</th>
<th>Initial Moment (kgf*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.6</td>
<td>840</td>
</tr>
<tr>
<td>2.3</td>
<td>496</td>
</tr>
<tr>
<td>0</td>
<td>-0</td>
</tr>
</tbody>
</table>

Table 3 – Initial bending moment on JE-22020.

The initial load can be explained by the friction forces on the structural component surfaces of the expansion joints such as hinges, pins and arms.

![Images from the EJ during the tests](image)

(a) (b)

Fig. 7. Images from the EJ during the tests.

The inclination of such curves represents the bending stiffening factor of the expansion joint. The average values for each test condition are summarized in Table 4.

Reviewing Table 4, in most cases, the stiffness factors increases as the pressure condition increases. This confirms the pressure stiffening effect.

In some cases (EJ-22015, -16 and -22) the operating pressure test shows greater stiffness values than design values,
while in expansion joints -27 and -29 the operating pressure stiffness value is lower than the non-pressure value. Since the data acquisition is not precise, these differences are possible the result of reading error or approximation. Some reading points may influence the deviation on the linearization used to determine the average stiffening factors. Besides these differences, the forces for each conditions tested are fully consistent with the internal pressure increase, as can be seen on Fig. 8, 9 and 10 (Annex A).

Table 4. Bending stiffness theoretical and test results.

<table>
<thead>
<tr>
<th>EJ</th>
<th>Stiffness Factors (kgf/m*deg)</th>
<th>Movement Test</th>
<th>Theoretical</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Design</td>
<td>Operating</td>
<td>No Pressure</td>
</tr>
<tr>
<td>JE-22015</td>
<td>1338</td>
<td>1361</td>
<td>1176</td>
</tr>
<tr>
<td>JE-22016</td>
<td>997</td>
<td>1022</td>
<td>812</td>
</tr>
<tr>
<td>JE-22017</td>
<td>1026</td>
<td>1006</td>
<td>818</td>
</tr>
<tr>
<td>JE-22018</td>
<td>1147</td>
<td>1107</td>
<td>844</td>
</tr>
<tr>
<td>JE-22019</td>
<td>1320</td>
<td>1172</td>
<td>879</td>
</tr>
<tr>
<td>JE-22020</td>
<td>1116</td>
<td>1025</td>
<td>900</td>
</tr>
<tr>
<td>JE-22022</td>
<td>1655</td>
<td>1714</td>
<td>1666</td>
</tr>
<tr>
<td>JE-22024</td>
<td>1145</td>
<td>1157</td>
<td>1094</td>
</tr>
<tr>
<td>JE-22025</td>
<td>1266</td>
<td>1250</td>
<td>1063</td>
</tr>
<tr>
<td>JE-22026</td>
<td>1180</td>
<td>1154</td>
<td>1085</td>
</tr>
<tr>
<td>JE-22027</td>
<td>140</td>
<td>109</td>
<td>135</td>
</tr>
<tr>
<td>JE-22028</td>
<td>125</td>
<td>103</td>
<td>102</td>
</tr>
<tr>
<td>JE-22029</td>
<td>144</td>
<td>98</td>
<td>175</td>
</tr>
</tbody>
</table>

The last column of Table 4 shows the theoretical cold stiffness factor calculated by EJMA code [1]. From this table it is possible to see that there are differences among the theoretical stiffness factor and those obtained from the movement test, these differences can affect the behavior of industrial systems.

The significant differences on Stiffness Factor, between the theoretical and the actual results obtained from the tests, occurred on EJ JE-22015 and -19 that presents values 16.4% and 14.8% higher than the theoretical ones. These differences become extremely high for the small diameter EJ: JE-22027, -28 and -29.

In the small expansion joints, since the design movements are very low (1.1°), only three readings were performed (0.5°, 1.0° and 1.5°), increasing the susceptibility to mathematical deviations.

Expansion joints JE-22015 and -19 are identical to EJ -20 and -18 respectively, but the stiffness factors are 20% greater on -15 in comparison to -20 for the design case, while for EJ -19 and -18 the difference is 15% for the design case.

Expansion joints JE-22015, -16, -17, -19 and -20 have the same theoretical bending stiffness, due to the fact that bellows design is the same. But, as we can see in Table 1, there are different hardware details involved, which would justify the difference in the values found for the stiffness factor.

**CONCLUSIONS**

This article presented the results achieved in the metal bellows expansion joint movement tests performed at the factory. A total of 13 expansion joints were tested, 5 of them were hinged and 8 were gimbal type.

The objective of the movement test was to check if there was any internal interference in the expansion joints final assembly that could limit the amount of movement that should be absorbed. In addition, it was possible to check if the real bending stiffness factors were close to those determined by the theoretical calculation by EJMA [2]. This is all important information since the turboexpander allowable nozzle loads are quite small.

The tests confirmed the importance of the pressure stiffening effect, and emphasize the necessity of finding out a better way to include this effect on bellows stiffening calculation and on the piping system simulation (flexibility analysis).

The friction forces are quite considerable and are directly related to normal force applied on the hinged pins. These pins are metal to metal contact without any special treatment, except for the hardcoating applied in some cases. This is especially important when stainless steel pins are required, to avoid the galling effect. In all tests, both carbon steel and stainless steel pins with or without hardcoating produced the similar behavior.

This pin friction effect as well as any other friction effect regarding expansion joint hardware is usually neglected in piping stress simulation. Since there is no reference in EJMA Code to this effect, there is no formal method to calculate or to simulate it. The tests showed that this value can be a higher value during the very first time the expansion joint is being moved in comparison to the subsequent movements. Dust, oxide or moisture can cause the system reactions to be higher. A friction reduction device is recommended, as well as some protection to avoid corrosion, dust and other undesirable components that could prevent the smooth movement of the expansion joint hardware.

The tests confirmed that the mechanisms (hinges), the inner sleeve, the insulation blankets and the anchor do not have interference which would prevent the correct performance of the expansion joints.

The test is quite simple and can be performed several times in a few hours. The device required to perform the test can be build in an ordinary factory facility.

Considering the advantage of confirm before installation that the EJ can properly absorb the design movements and since the tests have low complexity, perform the tests became a good practice in critical EJ systems, in order to avoid surprises during field operation.

Finally, there is another aspect that should be emphasized: the pressure stiffening effect can not be neglected when determining the bellows stiffness factors. Even though there is a
quite linear behavior in most of the cases; there is an important initial force normally not considered in piping stress analysis; this extra load may result in damage to the internal parts of turboexpander systems or any other rotating machine.

ACKNOWLEDGMENTS

The authors thankfully acknowledge the support of Teadit and Petrobras.

REFERENCES

ANNEX A

RESULTS FROM EXPANSION JOINTS MOVEMENT TESTS

Fig. 8. Applied moment on each expansion joint – Design load condition.
Fig. 9. Applied moment on each expansion joint – Operating load condition.

Fig. 10. Applied moment on each expansion joint – Non-pressure load condition.