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Segregation of Influences on Flexible Pipe Connectors (REPA) Force Under Field Operation Condition for Parabolic Trough Collector Plants

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Abstract. Flexible pipe connectors (REPAs) for parabolic trough collectors have been subject to numerous investigations and technical improvement at different test rigs worldwide. Still, REPAs remain a critical key component, that need further improvement to meet the life time expectations from power plants, especially at the comparably hot collector outlet locations. This paper analyzes the influence of the REPA setup in terms of pressure, temperature and the adjacent tubing (bottom connection) on the load cell readings at two REPAs. The investigations are performed using two flex hose assemblies, each composed of a corrugated hose and a swivel joint in combination with two different bottom connections. A set of five scenarios is investigated in order to conclude the most promising REPA testing setup with minimum mechanical loads on the load cell at the swivel joint from the bottom connection. This is not only relevant for testing ball joint assemblies and flex hose assemblies but gives a clear hint on how to integrate flex hose assemblies in power plant applications. It is found that the temperature has a comparably dominant influence in one of the bottom connections and thus impedes a load comparison of the two REPAs under testing. System pressure significantly increases the readings of the load cells, due to the fact that when pressurized, the flexible hoses introduce higher reaction forces especially when performing rotation cycle. Based on these findings the test rig at PSA will be adapted to execute tests of ball joint assemblies and flex hose assemblies in the near future.

INTRODUCTION

Flexible pipe connectors, often called rotation and expansion performing assemblies (REPA), are used in parabolic trough collector (PTC) power plants to connect the sun tracked absorber tubes to the fixed piping of the solar field. REPAs are among the most stressed and critical components of a PTC field [1]. During their service life they have to withstand at least 10'000 collectors tracking cycles. The REPA test rig operating at Plataforma Solar de Almeria (PSA) is geometrically adjustable in order to represent exactly the same REPA cycles as if the component was mounted on an operating solar collector. At the same time it reproduces real plant operating conditions in terms of motion patterns, heat transfer fluid (HTF) conditions (and up to 40 Bar and 450 °C) while enabling both, the application of silicone-based HTF or the commonly used synthetic organic fluid (biphenyl/diphenyl-oxide) [2]. During testing, the reaction forces of the REPAs are measured with load cells. The measurements serve to detect potential overload and load changes over time due to wear or component failure, for condition monitoring. This paper describes the systematic investigation and segregation of geometrical, thermal and hydraulic influences on the measured load with the aim to find a setup that enables the most meaningful load measurements during REPA testing. Different influences on the loads like system pressure, HTF temperature, and REPA motion have been segregated and recorded individually.

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REPA TEST RIG SETUP

The REPA test rig at PSA [2] consists of a closed circuit where pressurized HTF is circulated by a pump and heated with electrical tube heaters. This section is referred to as the HTF unit. The so-called kinematic unit (Figure 1, red rectangle) reproduces the movement of a receiver tube mounted in a parabolic trough collector, both in rotation and translation. There are two REPAs mounted to the kinematics unit that perform identical motion simultaneously. One REPA leads the circulating HTF up to the moving arm while the other brings it back down. Thus, HTF flows through the REPAs while performing accelerated mechanical cycles. The HTF unit is connected to both REPAs via tubes and ultimately with corrugated flexible hoses, one on each side (Figure 1, green dashed line). These hoses and tubes (Figure 1, green dashed and yellow dotted lines) are called bottom connections (in solar field this is the field piping connection). They serve to decouple the thermal expansion (lateral motion of 2-4 cm) of the tubes coming from the HTF unit to the kinematic unit where the REPAs are installed. This compensation of thermal expansion is needed because the REPAs must be mounted in a way that the lower bearing is a fix point, which mechanically forms part of the kinematic unit respectively a solar collector in a solar field.

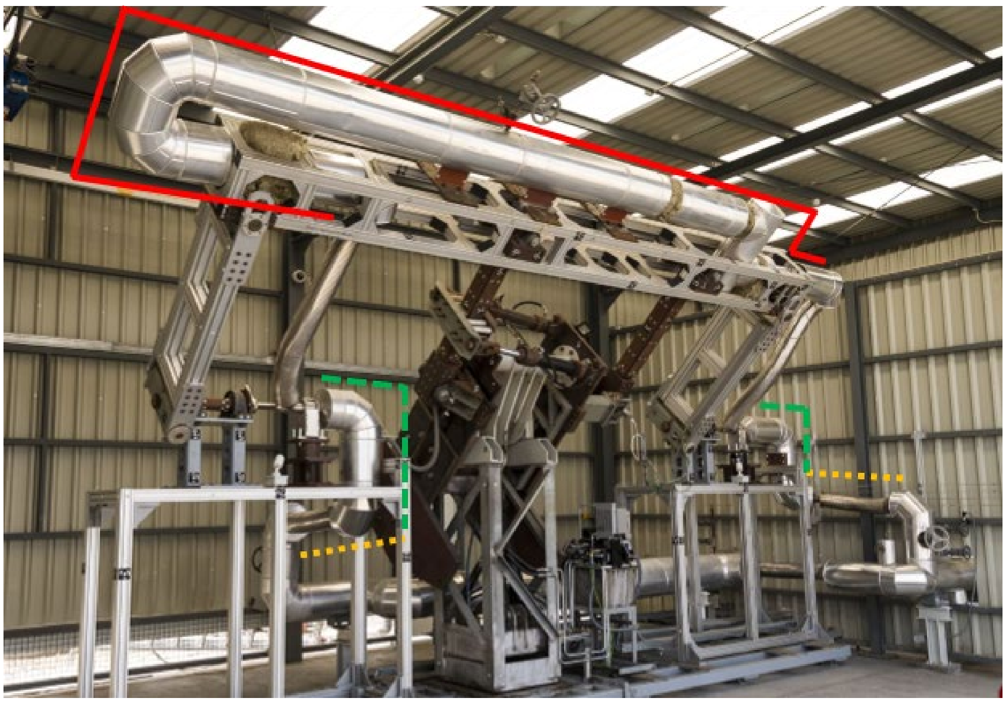

FIGURE 1. Overview of the kinematic unit with two flex hose assemblies mounted, left east, right west
solid red line: indicating the moving tube section,
green dashed line: indicating the bottom connections to both REPAs under testing,
yellow dotted line: indicating the orientation of the flex hoses as part of the bottom connection

REPA LOAD MEASUREMENTS WITH DIFFERENT CONFIGURATIONS AND OPERATION CONDITIONS

In the specific case of this paper, flex hose assemblies are under investigation. These components are hydraulically connecting a 2.5” diameter moving tube at the top with 2.5” diameter hoses at the bottom, while both swivel joints are mounted on top of multi-axis load cells, (model K6D175 10kN/1kNm, ME-Meßsysteme GmbH) as indicated in figure 2. Hence both, forces and torques introduced from the swivel joints to the support structure are measured in respect to all three spatial directions.

The REPA test rig enables testing of two REPAs under identical conditions simultaneously. One can see, that a REPA cannot be linked or flanged to another tube by means of a load cell for technical reasons, unlike two beams which can simply be connected to both sides of a load cell. Therefore, the load cells are located at the base of the REPA. However, this measurement approach is blind to load cancellation e.g. due to revers force or torque entry from both sides, as it leads to an underdetermined system of equations, and it cannot distinguish between the loads coming from the collector side and the ones coming from the bottom connection. This can be overcome by changing the boundary conditions. Following this approach, the influence of the bottom connection can be measured individually and be compensated or adapted, because these influences are independent from the REPA position, type and design, and only depend on the operation conditions. As described above, the bottom connection is connected to the REPAs with corrugated flex hoses, because these components are believed to perform the most mechanically efficient, decoupling while still conducting the HTF from one side to the other. Nevertheless, flex hoses exhibit changes in their reaction forces as a function of internal pressure, especially when mounted in a curved configuration as presented in order to e.g. cope with pipe offsets.

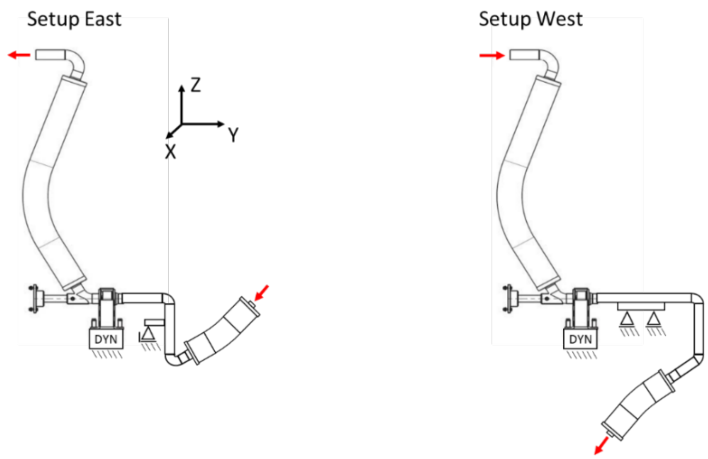

FIGURE 2. Schematic illustration of original eastern and western setup indicating the load cells' locations (DYN) and the guided bearings next to the swivel joints;

REPA Load Measurement Setup

The approach of testing two technically identical REPAs under identical boundary and testing conditions aims at achieving very similar results in the first place. Later on, when wear or imperfections come into play, differences are more likely to be observed.

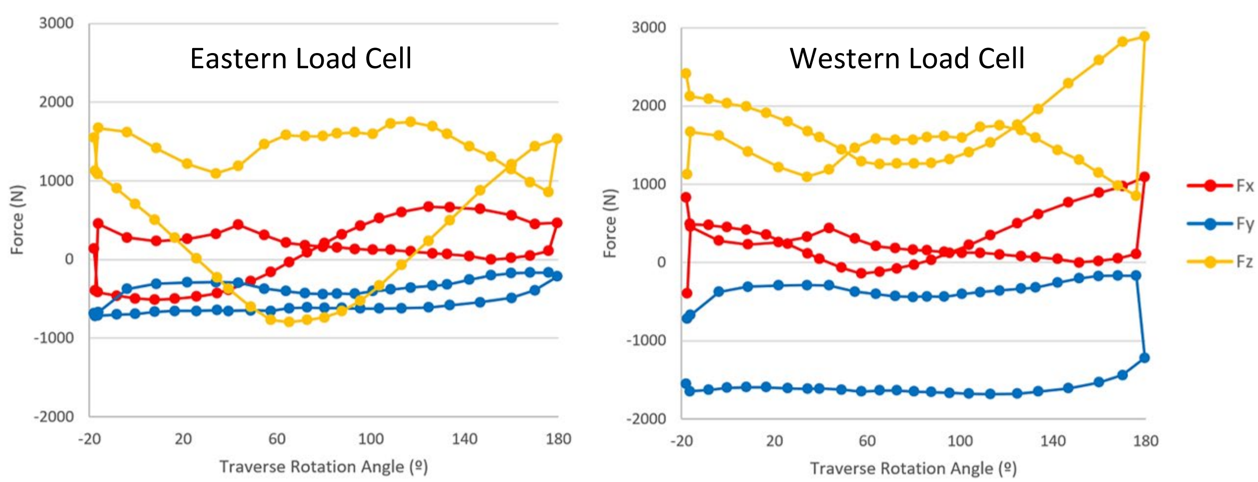

FIGURE 3. Load cell measurement results during rotation and lateral motion, showing very different load levels even though the REPAs are mounted in geometrically identical positions except for the bottom connection, which was originally believed to have a minor influence

The initial setup mentioned in this paper realized for the commissioning of the REPA test rig was featuring identical geometries of the REPAs, while the bottom connections were built somewhat differently on both sides due to limitations of surrounding structural items. The structural differences of the setups are depicted in figure 2. However, the influence of the bottom connections on the load measurements turned out to be in the same order of magnitude as the reaction loads from the REPA under testing. Figure 3 shows the different forces in the load cells over parallel rotation (-20° to +180° to -20º) and translation (-3º to 11º to -3º) movement respectively comparing the eastern and the western setups.

In addition to the basic configuration described above, in order to distinguish between loads from the collector side or from the bottom connection, a series of specific tests was performed, see Table 1. To perform these tests three different setups were implemented one after another by separating and hydraulically closing the pipes at the inlet and outlet of the swivel joint (Figure 4). The mounted flex hose assembly at the western side was mechanically and hydraulically modified and measured accordingly. Both setups 2 and 3 impede HTF circulation and thus HTF heating. Still, under this testing condition especially the piping geometry (REPA orientation) and pressure dependent influence of the bottom connection can be measured individually. Hence, the measurement results from setup 3 can later be subtracted from the super-positioned loads of the REPA and the bottom connection (setup 1), as those influences are independent from the REPA position, conditions and type.

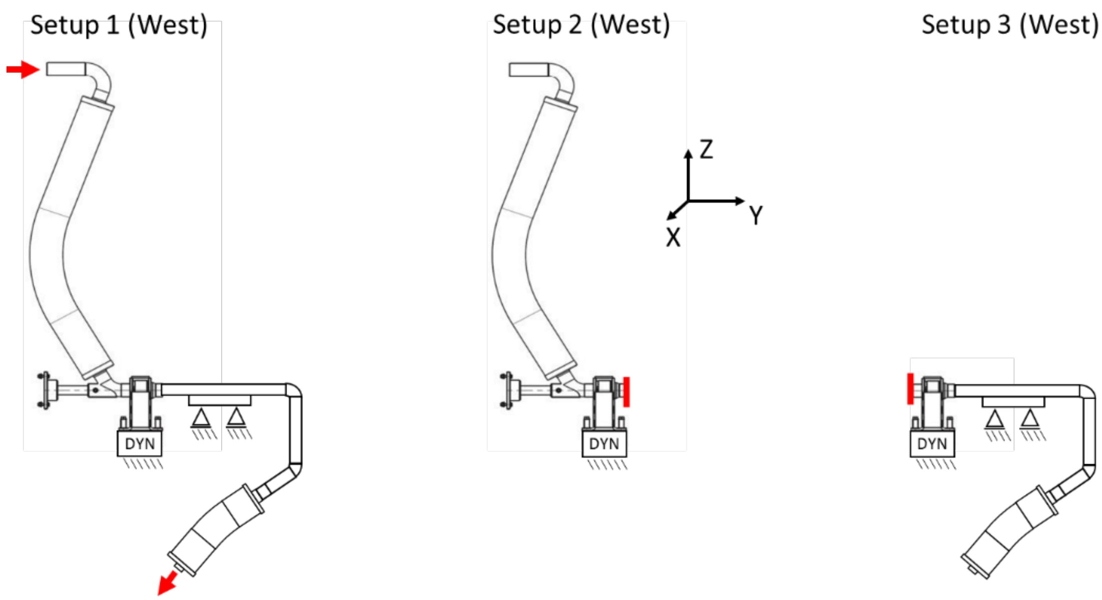

FIGURE 4. Schematic illustration of setups 1, 2,3 (west side as example) under investigation to measure forces from top connection side (2) and bottom side (3) independently, red arrows indicate the HTF flow direction, red bars indicate cut and closed tube connections.

In order to identify and determine the individual influence of pressure, temperature as well as the bottom connection and its geometry in the load measurement at the REPAs, five different test scenarios with three different setups were executed, see Table 1.

TABLE 1. Parameters and setup of the different test scenarios

Scenario	Motion Cycling	HTF Temp. °C	Pressure bar	Configuration	Investigating the influence of:
1	X	400	24	Setup 1	Normal operation
2a		t_{amb} - 400	19 - 24		Heat up
2b		400 - t_{amb}	24 - 19		Cool down
3a	X	t_{amb}	p_{amb}		no pressure
3b	X	t_{amb}	40		max pressure
4a	X	t_{amb}	p_{amb}	Setup 2	no pressure
4b	X	t_{amb}	40		max pressure
5a		t_{amb}	p_{amb}	Setup 3	no pressure
5b		t_{amb}	40		max pressure

RESULTS AND DISCUSSION

Motion cycles of the top connection (-20° to 180° and back) are performed in continuous motion as indicated in Table 1 and analyzed. Measurements are recorded every second. The results are presented in Figure 5. Only forces in z direction (vertical) are depicted since they are most pronounced and thus the most relevant. They enable a comparison between the maximum and minimum force in all five test scenarios for both REPAs side by side.

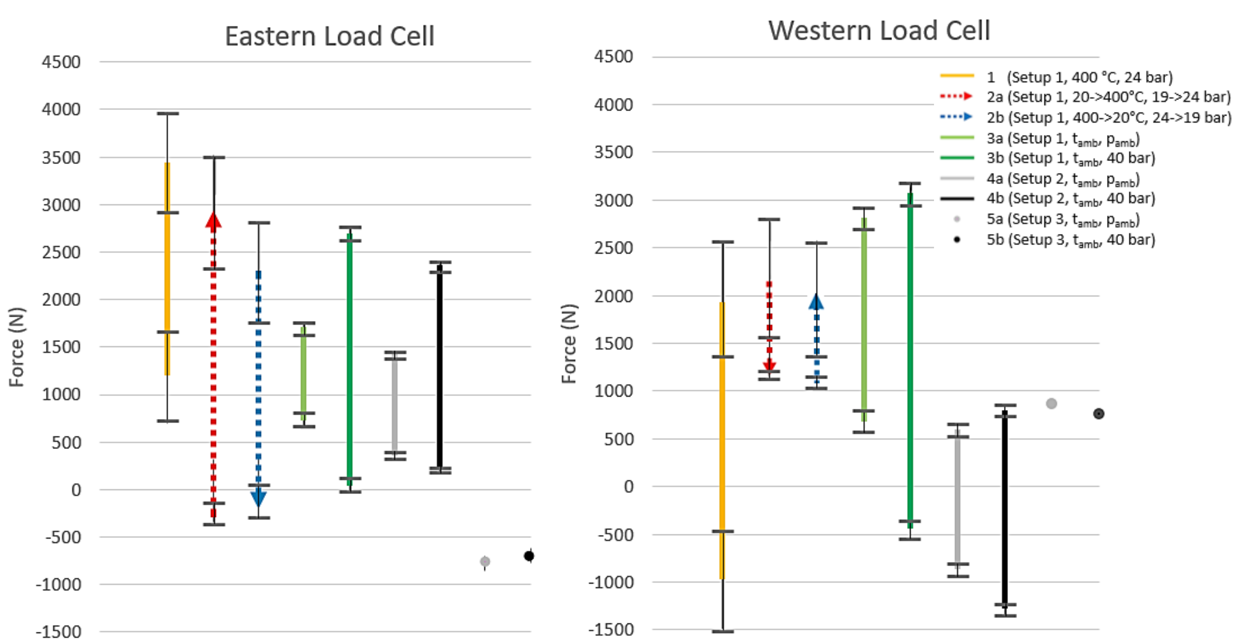

FIGURE 5. z-force (vertical) recordings for scenarios 1 to 5b at the eastern load cell (left) and at the western load cell (right) for full rotation cycles (-20° to 180°and back) of the kinematic unit grey error bars represent the accumulated uncertainties of the depicted max and min values.

Effect of Temperature

Scenarios 2a and 2b aim at isolating the effect of temperature on the force reading. Both scenarios were executed with the rotation arm in stow position at -20° (below northern horizontal position). The dotted lines represent the force range measured when heating the HTF loop up (2a) and when cooling it down (2b). The force change is indicated by the arrows. In the given rotation arm position, the REPA flex hose reaction forces have a component in z-direction reduced by sin (20°). Z-forces increase with temperature. Eastern and western side show significantly different results.

Temperature has a relatively low impact on the western side, decreasing from 2200 to 1200 N while it has a major impact on the eastern side that shows 2.6 times this difference, from -260 to 2940 N. This amplitude can be explained by different (non-compensated) thermal expansion related loads resulting from the pipe connections in combination with the floating bearings at the bottom connections (see effect of the bottom connections).

Effect of Pressure

Scenarios 4a and 4b aim at isolating the effect of pressure just on the REPA while motion cycling without the influence of the bottom connection. The z-force recordings during a single REPA rotation (forth and back / -20º to 180º) in scenario 4a (ambient temperature, no pressure) differ between east and west by about 30% in terms of max and min values while there is a mean value offset of app. 1000 N. The z-force recordings during a single REPA rotation in scenario 4b (20°C, 40 bar) differ between east and west by about 5% in terms of amplitude, while there is a mean value offset of app. 1500 N. Especially at 40 bar, the characteristics of east and west are similar, apart from the mean value offset. This offset can only be explained by an unidentified systematic uncertainty in the load cell reading.

Scenario 3 aims at recording the effect of pressure on the REPAs together with the bottom connections. Comparing scenario 3b to 3a, both load cells register a decrease of the minimum z-force values and an increase of the maximum force values. In both cases the overall amplitude during the motion cycle is increased. This is due to the effect that when pressurized, the flexible hoses of the REPAs and at the bottom connections introduce higher reaction forces. These forces are affecting the z-force measurements.

Effect of the Bottom Connections

When comparing scenarios 3 and 4, one can see that the eastern side shows minor difference in terms of amplitude and mean value offset while the western side shows much more pronounced differences. It can be concluded, that the western bottom connection has a larger influence in the z-force measurement than the eastern connection for both, amplitude and mean value.

Scenarios 5a and 5b aim at understanding the effect of pressure just on the bottom connections. The z-force recordings of the bottom connections with both REPAs disconnected in scenario 5a and 5b depict a 1500 N difference between east and west caused by the different bottom connection geometry only. One can see, that under the given bottom connection setup, pressure only has a minor effect on the force measurement. This is expected because there are rigid pipe connections with floating bearings between the flex hoses and the swivel joints at the load cells. Thus, the above described influence, recognized by the comparison of scenario 3 and 4, must result from the pipe connections with floating bearings.

Effect of Motion Cycling

Scenario 4a aims at analyzing the z-forces caused by motion cycling / during a single REPA rotation (back and forth / -20º to 180º) at ambient temperature, atmospheric pressure and without the influences of the bottom connections. The minimum z-forces registered are 390 N at the eastern and -840 N at the western load cell. This offset and the mean value offset of about 1000 N is unexpected and can only be explained with a systematic uncertainty in the order of magnitude of the expected sensor reading, as the REPAs and the geometry are identical. Especially the eastern positive reading cannot be mechanically explained otherwise. The amplitude on both sides differ by about 30 %.

Scenario 3a aims at analyzing the z-forces caused by motion cycling at ambient temperature and atmospheric pressure including the influence of the bottom connections. The minimum z-forces registered are 760 N at eastern and 710 N at the western load cell. These values result from the combination of the angle dependent REPA dead load and the forces from the bottom connection. The maximum sensor readings of the cycling are 1680 N for the eastern and 2780 N for the western setup 1. The amplitude of the sensor reading on the western side is more than two times higher than on the eastern sensor. One can see, that the uncertainty identified in scenario 4a is interfering with a second systematic influence caused by the bottom connection with the same order of magnitude in scenario 3a.

Uncertainty Analysis

The load cells present different systematic uncertainties, shown in table 2. The estimated impact presents a rating of the influence of the corresponding uncertainty. The combined uncertainties under the given circumstances are presented in figure 5 by the error bars.

TABLE 2. Load cells measurement uncertainty

Uncertainty	Approach	Value east	Value west	estimated impact
Zero signal when mounted, SF_0	measured	1 N	41 N	moderate
Relative hysteresis error, μ	meas. under stationary conditions			neglected
Relative creep 30 min., d_{cr}	<0.1% FS	<10 N		minor
Relative linearity error, d_{lin}	<0.1% FS	<10 N		minor
Relative repeatability error, b_{rg}	<0.1% FS	<10 N		minor
Temperature effect on zero signal at 20ºC, $TK_{0,20ºC}$	0.1% FS / K	(+/-) 0 to 580 N		major
Temperature effect on characteristic value, TK_c	0.05% RD / K	(+/-) 0 to 41 N		moderate
Difference in zero signal due to temperature hysteresis, $U_{0,vº}$	meas. under stationary conditions			neglected
Difference in zero signal after complete heating cycle, $\Delta U_{0,nc}$	measured	9 N	18 N	minor

FS: of full scale, being in Z axis 20 kN, RD: of reading [3]

Before and after a test, both load cells are mechanically disconnected at their top flange (swivel joint is lifted) and reset to a zero reading. The residual zero signal SF_0 value is registered. In addition, both load cells are loaded with a known calibration weight of 1249 N by means of a perpendicular point load at the center of the flange. The deviation from this weight is recorded and defined as $\Delta U_{0,nc}$, see table 2.

When carrying out measurements at ambient temperature, the combined uncertainty is quite low, as systematic uncertainties from creep, linearity and repeatability reach a total value of <±30 N, the previously determined SF_0 plus $\Delta U_{0,nc}$ account for <60 N, and temperature related uncertainties TK_c and $TK_{0,20ºC}$ are low. However, for the scenarios 1 and 2 at 400ºC, because of heat conduction to the sensors and despite the use of air coolers, the body of the load cells can reach up to 55ºC causing an important increase of the individual uncertainties $TK_{0,20ºC}$ and TK_c that scale with temperature. For instance, the west side load cell reached 49ºC while recording scenario 1b, resulting in a total combined uncertainty of 695 N of which 606ºN are temperature related.

CONCLUSION

In order to distinguish between the different influences in the REPA load measurement, two modifications of the existing setup have been investigated, compared and presented in terms of the maximum and minimum load values in z-direction. The REPA load comparison on both sides incorporating bottom connections is not possible, because the geometrically different bottom connections influence the load measurements in the order of magnitude of the actual measurement results. Therefore, one can see, that a direct comparison between both REPAs is only possible for setup 2 (scenario 4) where both bottom connections are disconnected and thus show similar force amplitudes. Still, an east-west mean value offset is evident which indicates an unidentified systematic uncertainty in the load cell readings.

It can be concluded, that mechanical REPA load measurements under realistic operation conditions including HTF flow must be corrected by the load influences from the corresponding bottom connections. These loads are introduced via the bottom connection and can be reduced to a certain level by designing the bottom connection with compensators. The presented bottom connections make use of flex hoses. It is expected to be beneficial to implement the shortest lever possible between the compensator (bottom connection) and the REPA avoiding the need for further structural elements that may again introduce unnecessary loads. Still, any used compensator will introduce significant loads to the REPA depending on its orientation, geometry and the system pressure. These bottom connection specific loads must be recorded separately (mechanically disconnected) prior to testing in order to exclude them from the REPA load reading analysis later on, as shown in scenario 5.

Mechanical REPA load measurements and comparisons require that the compared setups are identical in terms of REPA geometry/type and bottom connection characteristics. Thus, the two bottom connections of the PSA REPA test rig will be modified by placing the flex hoses as thermal stress compensators at the bottom connection, as close to the REPAs as possible. The setups shown in figure 6 have been found to be most suitable for both ball joint and flex hose assemblies, because they avoid supports and tube sections next to the load cells, that would cause mechanical influences and thermally induced stress. Moreover, the load cell temperature has an important impact in the measurement uncertainties. It is foreseen to install a cooling and heating sleeve in order to reduce the influence of the hot piping heat conduction on the load cells.

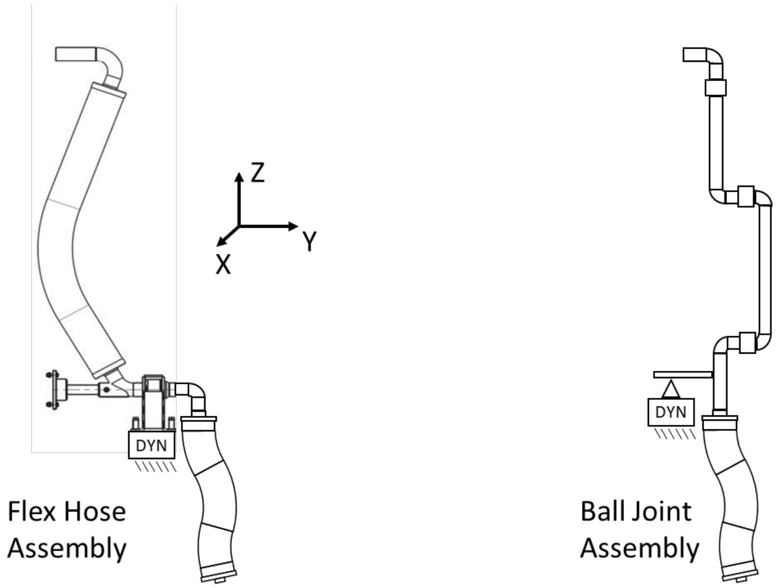

FIGURE 6. Schematic setup for future flex hose and ball joint assembly load measurements, with identical bottom connections and using flexible hoses as compensators

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REFERENCES

1 A. Plumpe, "Design of a Test Rig and its Testing Methods for Rotation and Expansion Performing Assemblies in Parabolic Trough Collector Power Plants," RWTH Aachen University, "Design of a Test Rig and its Testing Methods for Rotation and Expansion Performing Assemblies in Parabolic Trough Collector Power Plants," RWTH Aachen University, 2016

2 J. Leon, J. Clavero, L. Valenzuela, E. Zarza, C. Hilgert, W. Reinalter and A. Plumpe , "Test loop for inter-connections of parabolic trough collectors,", SolarPACES Conference 2017, AIP Conference Proceedings doi 10.1063/1.5067024, 2018, 030008, https://aip.scitation.org/doi/abs/10.1063/1.5067024.

3 ME-Messsysteme GmbH, k6d175 10kn/1knm. Product description and technical Data, ME-Messsysteme GmbH, 28.01.2020.