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Results of Molten Salt Valve and Flange Component Tests with the TESIS:com Facility

Niklas Carl Dicke[1, a)], Marco Prenzel[2, b)], Dirk Krüger[1, c)], Thomas Bauer[2, d)], Anne Schlierbach[3, e)], Jana Stengler[4, f)]

[1] *German Aerospace Center, Institute of Solar Research, Linder Höhe, 51147 Cologne, Germany,*
[2] *German Aerospace Center, Institute of Engineering Thermodynamics, Linder Höhe, 51147 Cologne, Germany*
[3]*German Aerospace Center, Institute of Solar Research, Paseo de Almeria 72, 04007 Almeria*
[4]*German Aerospace Center, Institute of Solar Research, Wankelstraße 5, 70563 Stuttgart, Germany*

a) Corresponding author: niklas.dicke@dlr.de
b) marco.prenzel@dlr.de
c) dirk.krueger@dlr.de
d) thomas.bauer@dlr.de
e) anne.schlierbach@dlr.de
f) jana.stengler@dlr.de

Abstract. This paper addresses the requirements for components in solar thermal power plants using molten salt as heat transfer fluid. For both line-focused and tower systems, operation requirements for various components are compiled from standards, publications, and operating experience. This also includes information on the typical sizes of the components. Based on the collated operating parameters, tests were carried out with valves and flange connections, provided by industrial partners, in the TESIS:com test facility. Shutoff valves without valve spindle heaters and bellows were tested primarily through continuous open/close cycles at temperatures between 290 and 560 °C. The tests were conducted in two different campaigns in which the valves were exposed to Solar Salt for 4.5 and 8 days, respectively. After the first test campaign, the knowledge obtained was used to develop an improved valve packing. In addition, a new development of flange connections was subjected to high temperature gradients (shocks) and freezing.

INTRODUCTION

Concentrating solar thermal power plants often use molten salt as storage and/or heat transfer medium. Especially equipping parabolic trough solar fields for the use with Solar Salt represents significant potential for reducing LCOE (levelized cost of energy) as low as 0.111 USD/kWh [1]. Compared to commercial trough plants using thermal oil, the use of molten salt can reduce plant complexity and increase efficiency. However, the molten salt medium and the higher operating temperatures place high requirements on the plant components. As part of the BMWi-funded project “MSComp”, the presented work summarizes the requirements for molten salt component tests for tower and trough applications. In addition, experimental results of loop tests with valves and flanges in operation with Solar Salt at the TESIS:com test facility are presented.

SUMMARY OF REQUIREMENTS FOR COMPONENTS IN SOLAR THERMAL POWER PLANTS

Component tests should represent the operation in solar thermal power plants as close as possible to the application. In the following, the general requirements of solar thermal power plants for the process components are summarized first. In addition to parabolic trough systems, the present work also focuses on tower systems, whereby the application area of a component is more decisive than the power plant technology itself. Subsequently, the individual requirements for components compiled from standards, publications and operating experience are discussed.

In general, components in the cold loop upstream of the receivers are operated with temperatures of 290 °C and pressures up to 40 bar (trough, Fresnel) [2, 3] or 80 bar (tower). In the hot parts of the loop, a maximum salt temperature of 560 °C, or up to 650 °C wall temperature of the receiver tubes, is reached [3]. The average flow velocities in line-focusing systems are 1 m/s to 3 m/s, whereas for tower receivers they are about 5 m/s. The latter are necessary to dissipate the higher heat flux densities at the tower receiver. With a projected lifetime of 25 to 30 years, a solar thermal power plant goes through 18,250 to 21,900 thermal load changes [4]. The average temperature gradients according to literature values are about 2.8°C/sec for towers [5]. However, higher gradients are possible during heating and cooling phases. The same applies in the event of an operational disturbance. Additionally, the number of load cycles can be significantly higher for receiver tubes, as cloud cover or defocusing can lead to further stresses. The wall temperatures can be considerably higher, as already mentioned above, than the fluid temperatures due to the concentrated solar radiation. In line-focusing receivers, the temperature differences between the wall and heat transfer fluid are considerably smaller than in tower systems due to the lower heat flux density.

The individual requirements for the components depend on their tasks and the planned operating time. The following sections address some critical components in solar thermal power plants and highlight the individual requirements.

Fig. 1 and 2 show the position of valves at the inlet and outlet of a parabolic trough loop. The valves in the plants are mainly of the type globe and butterfly with nominal diameters between DN50 and DN500. The valve cycles show a high variation according to their function and position. On the one hand, control valves in the area of thermal storage systems or headers reach up to 100,000 or more cycles [6]. On the other hand, shut-off valves (manual adjustment valves, globe valves) from the individual collector loops perform only <100 cycles over the entire lifetime of a solar thermal power plant.

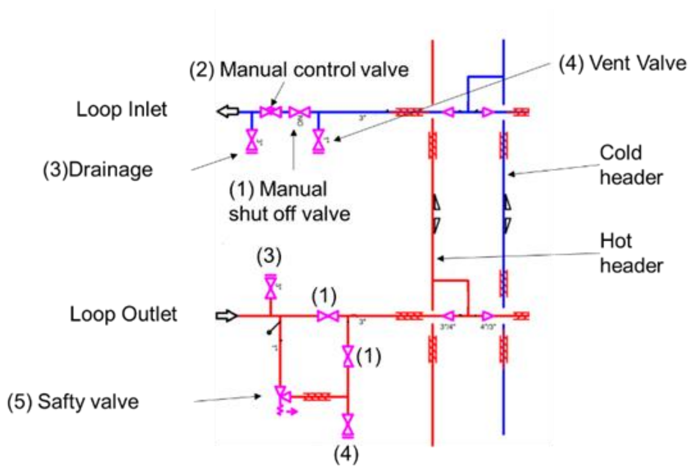

Figure 1. Drawing of typical positions of valves in a parabolic trough field

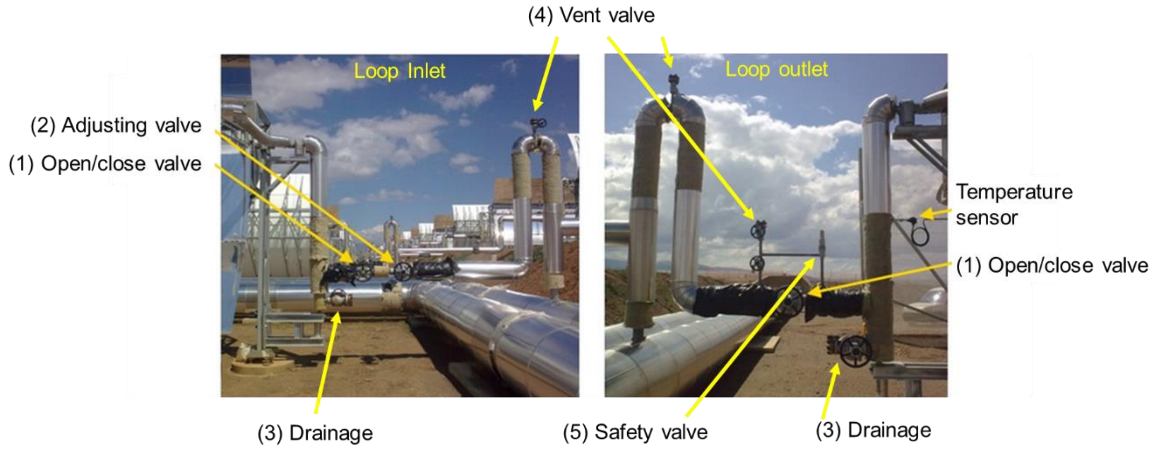

Figure 2. Example for positions of valves in a parabolic trough field (Photo: Schlierbach, Andasol 3 Marquesado Solar)

The power plant **piping** is an important component in the overall system. Typical steel grades for pipes on the salt side are, for example, 1.4571 or 1.4961 in the parabolic trough area and 1.4301, 1.4404, 1.4541, 1.4550 or 2.4856 in the tower area. There is always the risk of freezing, which is why trace heating and its monitoring are central to the longevity of the pipes. If the trace heating is insufficient and/or the insulation is poor, the instruments may freeze. Inadequate installation may lead to insufficient heat conduction due to poor contact between cable and component. This is often caused by cable lengths that do not match the component [7]. Receiver pipes (heat collecting element = HCE) can be permanently damaged by freeze/thaw events, when the thermal expansion of the pipes is prevented by frozen HTF plugs.

Pipe supports are another important element of the piping system, which are also insulated and partially trace heated to avoid cold bridges. Thermal expansions of the pipe must be compensated (e.g. by sliding or hanging pipe support). This requires designs that combine a support fixed to the pipe in a non-displaceable manner with a sliding bearing while keeping heat losses as low as possible. A good HTF pipe stress study is required for the pipe configuration and support design. Pipe supports can tilt, jam and cause damage due to uncontrolled movement caused by thermal expansion. As a practical advice it is recommended to mark the movements of the pipeline on the supports in cold and hot condition to validate the movement within the degrees of freedom of the pipeline calculation.

Critical components are **gaskets and flange** connections as the corrosive and hot molten salt can attack the materials (e.g. chemical reaction of molten salt with graphite gaskets from approx. 400 °C). In addition, frequent temperature changes lead to material stresses and, in the long term, to material fatigue, so that leaks can occur. Currently, flanged joints are avoided whenever possible and replaced by welded joints, since no manufacturer on the market guarantees tightness.

In parabolic trough systems, a **flexible connection** technique between the individual collectors or loop strings, for example by means of flexible pipe connectors (Fig. 3), is necessary. The connectors at both ends of the collector attach the moving collector to the static pipe. The so-called REPAS (Rotation and Expansion Performing Assemblies) accommodate the rotation of the tracking around the collector axis and the linear expansion of the absorber tubes due to thermal expansion. The entire temperature spectrum as well as the entire pressure spectrum of flow and return can occur. The necessary movement cycles during a planned operating period of 25 to 30 years are between 9,000 and 10,800 and have already been tested with liquid salt [8]. Here, the daily thermal load changes between 230°C and 580°C were not yet considered, as the tests were first run at a constant 230°C and later at 580°C. The number of cycles corresponds to those of the valves with 18,250 to 21,900 cycles during the entire service life. During a daily cycle of 0 - 175 degrees, the breakaway torque must be overcome during the start-up process for each tracking step, which takes place every 0.1-0.3 degrees. The REPAS may only be moved when the temperature is above the melting temperature of the salt used, because solid build-up can damage the corrugated hoses. Therefore, trace heating must be installed, which must work reliably on a permanent basis during the constant movements of the REPAS.

Figure 3. Flexible pipe connectors in parabolic trough collectors accommodate expansion motion (arrow above) and rotational motion (below). Photo: DLR, Plataforma Solar de Almeria owner CIEMAT

Pumps are critical components of a solar thermal power plant. Failure of a pump can, under certain circumstances, lead to the freezing of pipelines and other components. For this reason, redundant pump systems are often used in salt-controlled solar thermal power plants. Typically, pumps with long shafts (up to 15 m) are used in the salt tanks. Pump tests have shown that even with many hours of operation and frequent load changes, there is no damage to the sleeves and bearings [9]. The requirements for pumps in terms of temperatures, mass flows and pressures are determined by the respective area of application. In solar thermal power plants, there are salt pumps in the cold tank to convey the heat transfer medium to the receivers, but also in the hot tank to supply the steam generators with salt. Typical mass flows are in the range of 130 kg/s to 1,700 kg/s [10]. In tower systems, which are drained daily, load changes occur more frequently for the pumps in the supply line. This results in approximately 90,000 to 110,000 operating hours with 18,000 to 20,000 thermal load changes for a service life. However, major parts of the pump are constantly heated by the salt, so that the temperature gradients are low. On the other hand, in undrained trough systems, the pumps are often in continuous operation. The same applies to the pumps that ensure the supply of hot salt to the steam generators. These are also in operation between 18 h and 24 h a day due to the night storage operation. This results in between 165,000 and 262,000 operating hours.

TESTING OF VALVES AND FLANGES

In the first test campaign, three flange connections and two shut-off valves with packings (pneumatic and electric actuator) were connected in series (see Fig. 4). The test plan was developed to take the requirements for both components into account.

The two DN50 globe valves of the type HD2000 200LS were delivered by the company Stahl-Armaturen PERSTA GmbH to obtain a better understanding of the stresses and resulting degradation of valves in CSP power plants and for developing a cost-efficient solution. The packing of the valves consisted of graphite sealings with an envelope of a material with high resistance again hot salt (Boron nitride fleece and mica with graphite core). The valves were delivered without valve spindle heating and bellows to achieve lower investment costs.

The component test section of the TESIS:com facility consists of a DN50 pipe loop equipped with thermal insulation and trace heating. Components to be tested are welded or flanged. Required measurement and control instrumentation is available on site and is readily installed on the components. Solar Salt (60% $NaNO_3$, 40% KNO_3) is fed into the test section from a hot and/or a cold storage tank. TESIS:com can be operated at temperatures between 290 °C and 560 °C and produce mass flow rates from 0.5 kg/s to 8.0 kg/s. In addition to tests with constant supply temperature and mass flow, TESIS:com is also used to perform experiments with mass flow rate and temperature ramps as well as temperature shocks of over 100 K/s [11].

Within the first test campaign the two valves (and flanges), were exposed to Solar Salt for about 4.5 days. After successful function and pressure testing, 10,000 complete opening/closing cycles were scheduled per valve.

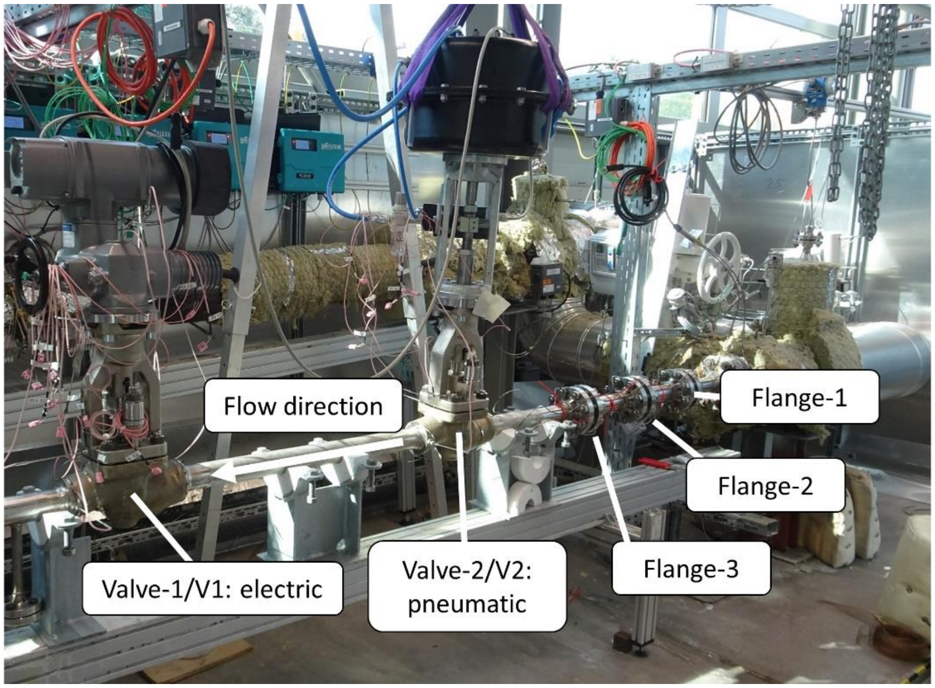

Figure 4. Test set-up of first test campaign without insulation (Photo DLR)

There was no waiting time between valve actuations. Initially, 5,000 cycles per valve were carried out at 290 °C. No leakage occurred during or after this test segment. Directly afterwards, i.e. without maintenance measures, valve cycle tests at 560°C were started. Leakages were detected on both valves after approx. 160 cycles. The leakage could be attributed to the fact that during the cycles at 290 °C, temperatures in the valve packing area were below the melting point of Solar Salt. For this reason, salt crystallization occurred and the solid salt crystals graded the spindle as well as the packing of the valves during cycling. At the 560 °C tests, the temperatures in the valve increased above the melting temperature and molten salt mixed with graphite leaked out. Figure 5 displays the temperatures measured at the valve. While Tv15 was inserted close to the salt flow, Tv16 was positioned just above the valve packing and Tv19 was measured on the valve spindle with slightly more distance to the packing. The pneumatic valve suffered stronger abrasion, probably due to the faster movements of the spindle.

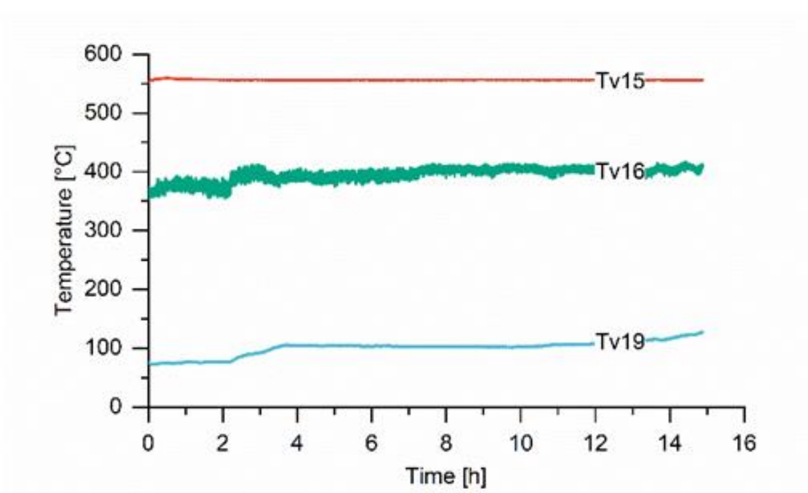

Figure 5. Temperatures at various positions during valve cycle tests at 560°C salt temperature

After a packing exchange, the test was repeated with the same electrical valve and spindle, this time immediately at 560°C. The pneumatic valve was excluded from the second test run, because the damage to the spindle was found to be too significant. 1,300 cycles were performed before a leakage was detected. The leakage point of the salt was, as in the first tests at 560 °C, the annular gap between the spindle and the packing. At the exit point, abrasion from the graphite packing was found in addition to salt residues. The cause of this defect is seen first in the abrasion of the envelope and then in the reaction of graphite and molten salt at temperatures >400°C.

After the first tests in the TESIS:com facility, PERSTA used the acquired knowledge to develop a more resistant packing material. After successful oven tests, in which the new packaging material was stored in hot Solar Salt for about six months, a second test campaign was started in the TESIS:com plant. This time, two electric valves were installed inside the test loop. Pneumatic valves were not used because, as already mentioned, their short actuating time places an additional load on the valve packing. The test setup was similar to Fig. 4, but no flanges were installed and tested this time. In addition, the design of the insulation and trace heating was improved so that temperatures at the packing remained above the freezing temperature of at all times and a crystallization of molten salt in the stuffing box could be prevented.

The second test campaign ran for about 8 days and both valves performed the planed 350 open/close cycles. A waiting time between valve actuations has been incorporated to keep the contact time with Solar Salt high but at the same time reduce the number of cycles. In this way, the open/close cycles performed better reflect the actual number of shut-off valve actuations in solar thermal power plants. During the second measurement campaign, the valves were subjected to constantly changing temperatures between 290 and 560 °C. Both valves completed the 350 cycles without leakage or other irregularities.

At the time of writing, the valves are being prepared for examination by PERSTA. This allows a closer inspection to see if the improved packings show any signs of wear. Regardless, the results are encouraging for the use of such valves (without extra spindle heating and bellows) for certain applications in solar thermal power plants. As mentioned above, shut-off valves used in the collector loop of trough systems perform < 100 cycles over their entire lifetime. Since tower systems are drained daily, the shut-off valves installed in the collector section are usually also actuated once a day, excluding days for maintenance. With reference to the improved packing (second measurement campaign), at least one year's operation was successfully simulated with the tests in the TESIS:com plant.

The three flange connections tested in the first measurement campaign (see Fig. 4) were developed by KLINGER Kempchen GmbH in Oberhausen specifically for rapid temperature changes in solar thermal power plants. The development originated shortly after the commissioning of the TESIS test plant due to leaks occurring at the flange connections as a result of rapid switchovers and temperature changes. In order to test the innovative flange connections in this respect, temperature ramps and shocks as well as a freezing test were performed with the TESIS:com facility. The shut-off valves were 100% open during these tests. First, three temperature ramps with gradients of +/-5 K/min, +/-10 K/min and +/-20 K/min, respectively, were performed between 290 °C and 560 °C. No irregularities or leakages at the flange connections were detected during or after this experiment. Subsequently, a total of six temperature shocks with gradients > 100 K/s were carried out, also between 290 and 560 °C. After the first three shock tests, minimal leakage occurred on two of the three flange connections. As a result, the gaskets were replaced, mounted with an increased contact pressure and the remaining three shocks were carried out. This time, no irregularities or leakages were detected during or after the tests. Finally, a freezing test followed in which salt was deliberately frozen inside the flange connections. The freezing test also remained without any irregularities or leakages. It is therefore concluded that the freezing test did not result in any damage to the seals. Since the tested flanged joints have withstood temperature ramps, a freezing test and, with one exception, extreme thermal shocks, their use may be viable for some applications in solar thermal power plants. For instance, flange connections can allow easier accessibility to components for maintenance purposes. The test results show that the flanged joints by KLINGER Kempchen GmbH, when properly installed, can provide a tight connection even under difficult operating conditions.

DISCUSSION

The results of the conducted test series reveal that certain operation conditions present a high risk of components being damaged. For valves, these are primarily the number of actuations, the actuation speed and the operating temperature. In the case of flanged connections, rapid temperature changes in particular are a major stress. Thus, this work highlights the importance of component testing under application- and component-relevant operating conditions.

The available standards for component design and testing do not reflect the actual operating conditions in solar thermal power plants with molten salt. In this case, the application of the standards does not guarantee the reliable functioning of a component. For instance, mandatory instructions for pressure tests of industrial valves are specified in EN 12266-1 [12]. The test procedures proposed according to EN 12266-1 are carried out at a temperature between -5 °C and 40 °C. Gas or liquid is stated as the test medium, but not further specified. Flanges and gaskets are calculated and designed e.g. according to EN 1591-1 [13]. However, no leakage tests are required before the use in a plant. Hence, experimental investigations of components, as presented in this work, are fundamental for the development of improved standards, which explicitly address the conditions in solar thermal power plants.

The key findings on valves derived from the tests conducted in cooperation with PERSTA are summarized in the following: Valve tests and especially the number of valve cycles should reflect the application of a valve in a solar thermal power plant. The results show that valves without spindle heating and bellows can withstand the lifetime amount of open/close cycles in a trough collector loop. In terms of the collector section of a tower system, it has been proven that the valves can at least withstand the number of cycles performed in one year. While valve suppliers may take an annual revision into account, solar field suppliers rather plan to operate the plant continuously without releasing the salt or annual maintenance. Maintenance-free or long-lasting valves and other components are thus of advantage and should be the development goals. Moreover, the actuation speed appears to be crucial to the longevity of the valve packing. Thus, either electric valves should be used or the actuation speed of pneumatic valves must be reduced deliberately. Shut-off valves are mostly in a fully open or closed position. In this case, an additional back sealing, as included by the PERSTA valves, helps to reduce the contact time of molten salt with the packing. With a back sealing, the plug closes the path to the valve packing when the valve is fully open. Nonetheless, contact of molten salt with the valve packing cannot be avoided entirely. Hence, the resistance of the sealings envelope against molten salt is of great importance and needs to be tested in an adequate test procedure. The valve tests have also highlighted that well-designed thermal insulation and trace heating are required. Both need to be well adapted to the valve design so that the heating is sufficient to ensure that salt is always in liquid state but also to avoid overheating. As this depends on the individual valve design, the setup of the heating and insulation should be specified or delivered by the valve supplier. In addition, a temperature sensor near the valve packing simplifies control of the trace heating system and increases reliability.

In the case of the flange connections, the tests have shown that they can withstand the difficult boundary operating conditions (e.g. dynamic loads, salt freezing). The correct assembly with suitable contact pressure seems to be decisive for the tightness. However, before flange connections are actually increasingly used in solar thermal power plants, the manufacturers must guarantee the tightness or be liable for malfunctions. For this reason, further tests are certainly useful to improve the functionality and to convince contractors of the reliability. It would also be of interest to conduct tests in which flanges are not only subjected to thermal loads, but also to superimposed mechanical stresses.

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