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Analysis of vacuum evolution inside Solar Receiver Tubes

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Abstract

In parabolic trough technology, the components used as solar receptor is formed by a steel tube confined inside a glass chamber. The space between both tubes is evacuated during the manufacturing process in current concepts. A new concept of absorber tube, currently under demonstration stage, HITECO, is based on the concept of dynamic vacuum, where the gas evacuation is produced in the solar field during the start up.

The gassing and the outgassing processes are the main mechanisms controlling the equilibrium pressure and the gas composition in high and ultra-high vacuum systems. In the solar absorber tubes the mechanisms that control the condition inside the vacuum chamber are adsorption, absorption, desorption, permeation and leakage. All these phenomena have been analyzed in detail in current paper in order to define the performance evolution of absorber tubes placed in commercial solar fields.

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Keywords: Leakage; Permeation; Outgassing; Adsortion; Absortion; Desorption; OPEX.

1. Introduction

HITECO (High Temperature Efficient Collector) project is aimed at the development of a new solar receiver concept, which integrates several innovative concepts in its design [1, 2]. This new solar receiver tube, for parabolic trough technology, enables having a continuous chamber with the length of a semicolector. This system works as an

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open chamber where pressure inside can be managed by dynamic vacuum operation. The vacuum level and the gas composition inside the chamber are monitored and preserved during operation with minimal energy losses.

Due to the relevance of the vacuum chamber in the new concept, and the importance of the particular processes taking place under such conditions, it has been analyzed the effects influencing the vacuum level and its composition: outgassing, leakage and permeation. These effects turn out critical because of their impact in energy losses and therefore to the overall efficiency of the collector.

2. State of the art and current vacuum strategies

The evacuated tubes, nowadays used in commercial solar fields, follow the concept of a close chamber in which is done a vacuum (of around 10^{-4} mbar) in factory. The performance of this tubes is committed to keep the system in perfect working conditions for not reduce the performance. The more common fail are the increase of pressure in the chamber because of breakage in the sealing, the breakage of glass with total loss of vacuum and the permeation of H_2 with the modification of the composition and pressure in the chamber. In all these cases the efficiency decreases radically, making unacceptable the operation on field according the standard evaluation procedures [3], [4].

3. Dynamic vacuum in HITECO concept

3.1. Concept definition

The idea under HITECO project is to produce a simpler, more reliable and efficient solar absorber tube. Along these lines, one of the ideas is to be able to operate the collector at relatively high pressure level, which essentially leads to similar heat losses, but with a significant simplification in the design and its maintenance.

In current absorber tube concepts, the vacuum in the chamber is produced during the manufacturing process by evacuation of the gasses located inside the chamber, followed by an outgassing process at high temperature. These devices are then isolated, maintaining theoretically these working conditions by the use of a GTMS (Glass to Metal Sealing) union.

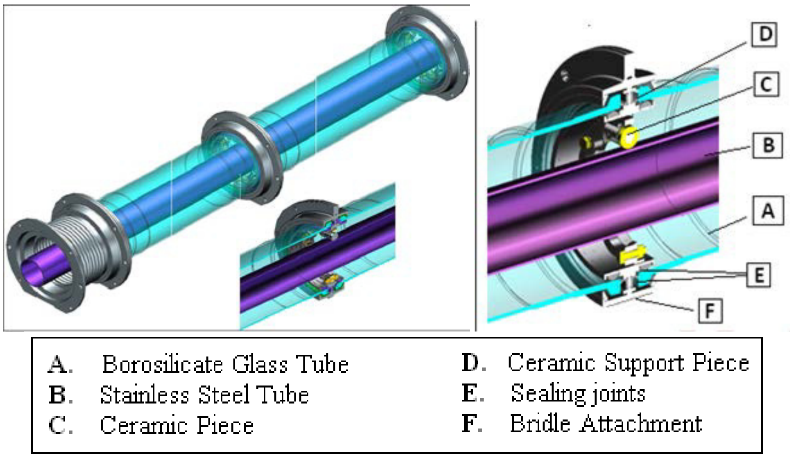

Fig. 1: Sketch showing some of the main concepts included in HITECO design.

HITECO proposes a different concept, since the vacuum is produced in the solar field, the composition of the chamber and its pressure are managed within each semicolector and the sealing is performed by simple and inexpensive elastomeric components (Fig. 1). Besides, the new concept operates in less restrictive conditions, since it is possible to obtain similar heat losses levels by working at 20 mbar pressure of Kr instead of the common practice in other concepts of 10^{-4} mbar of air. In other words, this new concept would lead to similar heat losses working at pressure levels 20.000 times higher, which directly impacts in design restrictions and operation.

3.2. Mechanism involved in the process

Unlike current absorber tube concepts, HITECO requires the control and definition of some critical parameters involved in the gassing–outgassing equilibrium. Despite that, the control in a solar field is simple, being the definition of conditions and factors involved in this equilibrium discussed below:

Leakage: It is related to the capacity of the seals to avoid the entrance of gasses through the space between seal and the gap. This is given by the hardness of the sealing, the contact area with the gap and the forces applied over the sealing. Therefore, it is necessary to reach adequate roughness properties in both faces in order to avoid any path for gas entrance from the atmospheric pressure to the vacuum chamber. Another factor directly affecting the sealing capacity is the orthogonal force between sealing and the metallic or glass wall.

The temperature increase in the vacuum chamber does not directly imply higher leak rates, but it has an indirect effect in leakage due to the different dilatations of the various components (thermal stress of materials), produced by their different thermal expansion coefficients.

Permeation: It is related to the pass of gasses through the seal joints. This characteristic is given by the material in which the joints are produced and the temperature of the sealing during operation. This factor is relevant in HITECO since the sealing joints are heated by conduction.

Outgassing: It is defined as the release of gasses from a surface when it is under vacuum conditions. The outgassing depends on the temperature and level of vacuum and is related to the release of species adhered to the surface by mechanism of adsorption and absorption.

4. Vacuum analysis and results

This study is focused on the analysis of the behavior exhibited by the new vacuum chamber, in order to validate the concepts included in the HITECO design. To achieve this objective, different variables have been considered: a) the leakage of elastomeric seals, b) behavior under static or dynamic vacuum processes and influence of the temperature chamber in the outgassing process and c) sealing components permeation. All these processes generate variations of pressure in the chamber, which are quantified by the measure of the vacuum flow rate Q_{tot}. The vacuum flow rate characterizes an increase in pressure as a function of the chamber volume, and is usually expressed in mbar· l /s.

Two different prototypes have been produced for carrying out the experiments included in the project scope. They have been designed following the requirements of the HITECO tube concept [5]. Prototype (A) consists of a chamber with a maximum volume of 0.02 m^3 (with the absence of internal steel tube) and Prototype (B) consists of a 12 m long chamber with a volume of 0.2 m^3, also capable of being heated by electric resistances.

4.1. Sealing assessment: leakage effects

The effect of leakage in HITECO solar receiver has been tested in the several configurations (Fig. 2), spanning a number of combinations of total volume, as well as exposed areas of glass, steel and elastomeric material and number of sealing joints.

Please note that the leakage analysis is done by avoiding other parameters that have any influence in Q_{tot}: it means to work at low temperatures (therefore we assume Permeation ≈ 0) and with a clean chamber (Outgassing ≈ 0). According to these assumptions, it has been performed several successive pumping processes in the vacuum chamber, in order to restrict the effect of outgassing, until reaching steady state conditions.

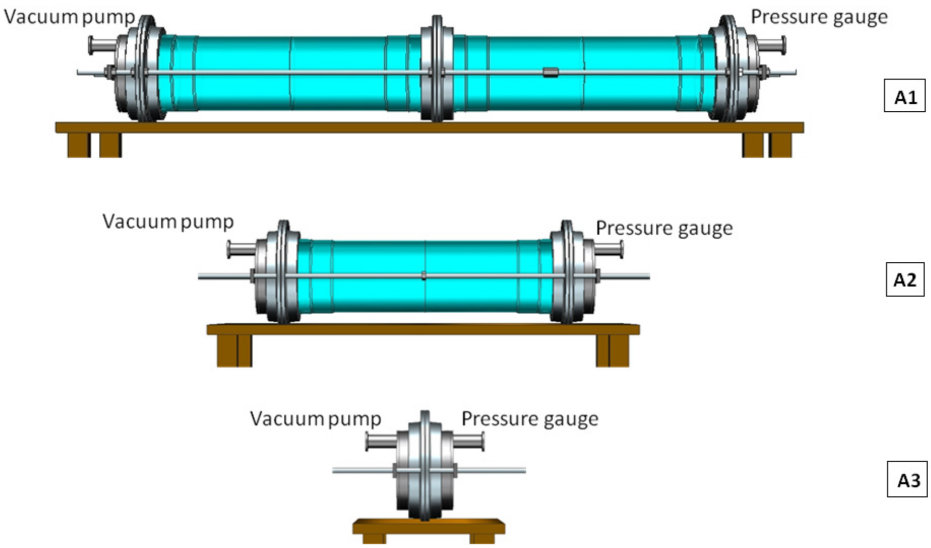

Fig. 2: Prototype A for leakage tests. Case A1: 27.4 liters and 6 joints. Case A2 13.4 liters and 4 joints. Case A3 1.9 liters and 2 joints

Since there are no other factors effecting on Qtot at room temperature, and the permeation through rubber seal is negligible at this temperature, leakage on these configurations was analyzed through based on the total vacuum flow rate, i.e., Leakage ≈ Q_{tot}.

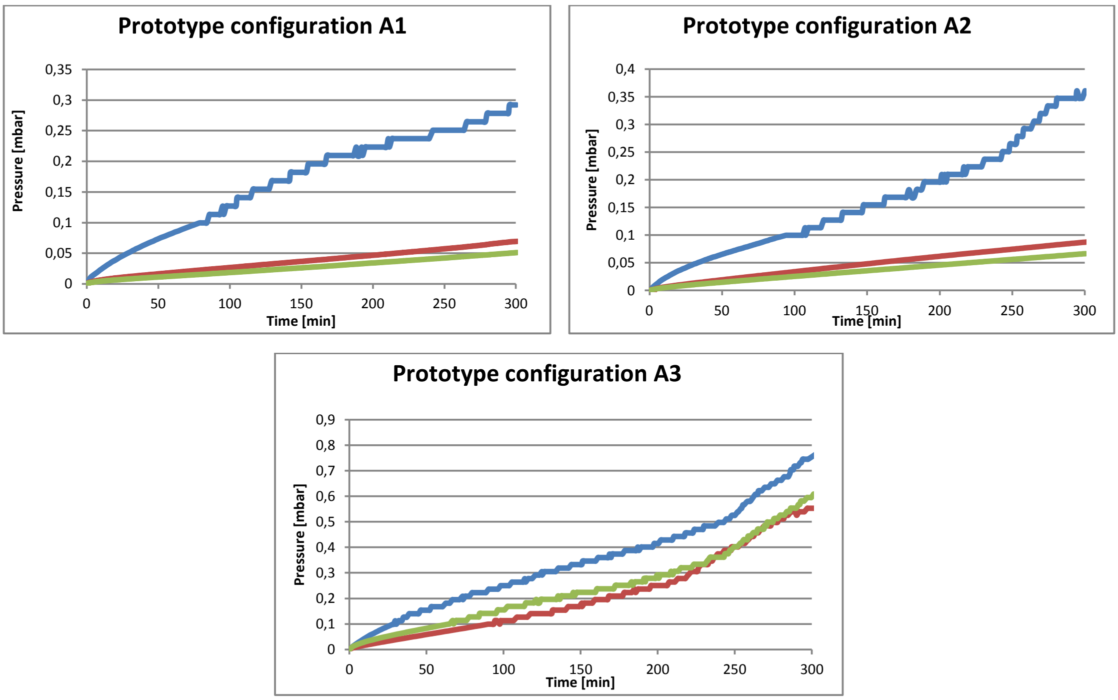

Fig. 3: Pressure in vacuum chamber in prototype A before (blue) and after (red and green) outgassing process at room temperature.

The results shown in Fig. 3 conclude that leakage is roughly represented by straight line, with roughly constant slope. The leakage values for every configuration and considering the number of seals are shown in Table 1, which yield a leakage level per seal at room temperature of around $1.1 \cdot 10^{-5}$ mbar · l/s.

Table 1: Leakage by seal measured in every prototype configuration

Prototype Configuration	volume [liters]	Number of seals	Total Leakage [mbar·l/s]	Leakage by seal [mbar·l/s]
A1	24.70	6	$6.72 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$
A2	13.40	4	$4.54 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$
A3	1.92	2	$2.17 \cdot 10^{-5}$	$1.1 \cdot 10^{-5}$

In current concepts the union made by a GTMS (Glass To Metal) procedure has a tightness in the range of 10^{-9} mbar·l/s. It means a very high rate compared with polymeric joints. In any case, the conditions of HITECO in which is done a repumping each six months (aprox) and not trying to sure 25 years of operation allows not working with this technology reducing the costs.

4.2. Sealing assessment: permeation effects

The only components with relevant effect on the permeation are the sealing joints, manufactured with an elastomeric material (Viton) being negligible the effect in glass and metal.

The elastomeric material has been tested in order to define the permeability of the material through a sample in a range from room temperature up to around 180ºC, considering a pressure difference Δp of atmospheric pressure on one side and high vacuum on the other side of sample. The measured gas permeability coefficients (F) are shown in Fig. 4. This coefficient depends not only on the material properties and temperature but also on the area of transfer (A) and the width of the material (x) as it is shown below:

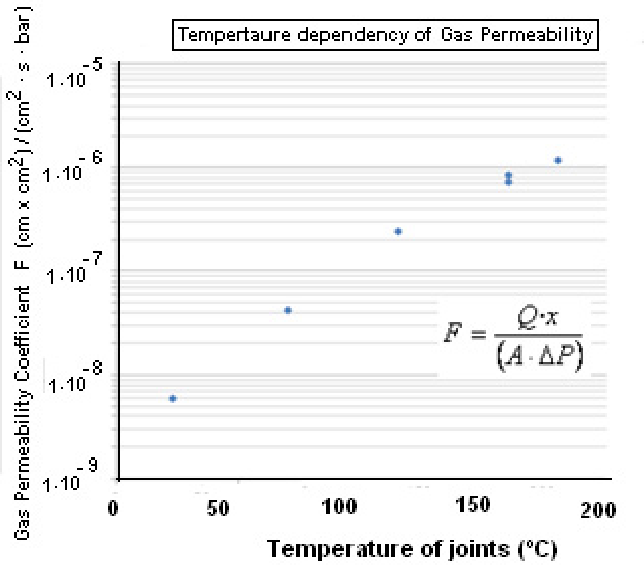

Fig. 4: Temperature dependence of the gas permeability coefficient.

It can be inferred from Fig. 4 that the permeability coefficient of this elastomeric material highly depends on temperature. Six seals were installed in prototype B measuring the influence of temperature in sealing permeation by taking into account the leakage values already analyzed in prototype A. The experiments performed in prototype B were aimed at measuring the pressure evolution in the vacuum chamber at different temperatures for testing the influence of the parameters of sealing joints (material, area, width and temperature) in the global permeability of the system.

The pressure flux, Q_{tot}, is defined as the pressure rise during the test Δp, being V the total volume of the vacuum chamber, t the test time and n_{seals} the number of seals in the system under analysis. These results are presented in Fig. 5 and show that at high temperatures this is main factor contributing to increase pressure rise in the vacuum chamber. Acceptable permeation rates are the ones below 140ºC on the seals, and this information was crucial during the design of the components involved in the set.

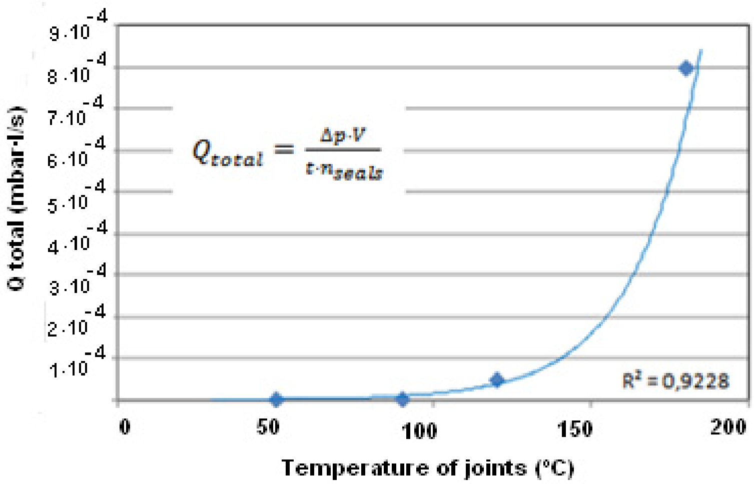

Fig. 5: Impact of joint temperature on HITECO receiver tube permeation rate.

In current concepts, [3], [4], there is no permeation through the typical GTMS, so this factor is not considered as part of the mechanism for increasing the pressure. Other kind of permeation is the pass of H_2 from the thermal oil cracked to the vacuum chamber changing its composition. This last effect happens in both concepts but HITECO has the chance to remove it by the regular repumping recovering the initial performance.

4.3. Outgassing process and its effect

The analysis of the outgassing process in the pressure evolution has been performed by considering the previous values of permeation and leakage as baseline for a clean chamber and, as a consequence, the target to reach during the cleaning process. The outgassing process is speeded up by operating the vacuum pumps and increasing the temperature of the surfaces which are releasing gasses. We considered moderate temperature increases to avoid thermal stresses on the surfaces (which could affect the selective coating on the inner steel tube) and peaks of pressure that could lead to sudden release of species in the vacuum chamber. During the testing process in the HITECO receiver tube presented in Fig. 6 we observed specific temperatures where pressure peaks (always below 10^{-2} mbar) appeared, so we maintained the temperature constant until these peaks disappeared. This effect is related to the outgassing of species at different temperatures and in different desorption levels on chamber surfaces.

The various panels in Fig. 6 provide a good characterization of the outgassing in the vacuum chamber, showing that the peaks last for around 1.5 hours and five peaks are found up to 450ºC. A total of 7.5 hours are needed to obtain an appropriate outgassing of a continuous vacuum chamber. In order to decrease the outgassing rate to negligible levels (at least one tenth below permeation or leakage), it is necessary to keep the pumping for 2 hours at maximum temperature with a pressure level of 10^{-4} mbar.

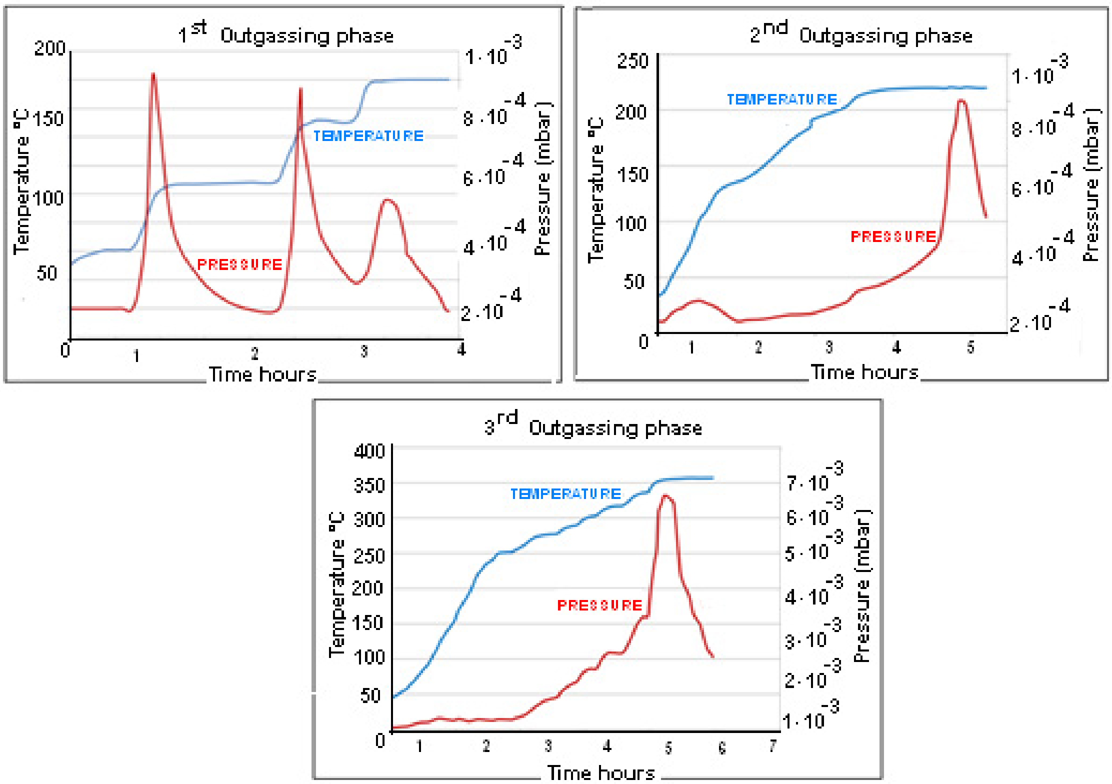

Fig. 6: Receiver temperature (blue) and vacuum chamber pressure (red) while pumping down at (a) 105ºC, (b) 265ºC, (c) 400ºC

The outgassing in current concepts is done during the manufacturing process, being, according to the specification of the suppliers, good enough for not increase the pressure at high temperature conditions (420ºC).

5. Definition of operation conditions and its performance

5.1. Operative situations in a solar field

As previously discussed, the elimination or mitigation of thermal losses due to thermal convection is the main purpose of evacuating the vacuum chamber. In a typical solar plant, solar absorber tubes work initially around 10^{-4} - 10^{-3} mbar of total pressure, although, it is currently not clear how these pressure levels change with time, as well as the composition of the gas in the chamber. Some effects leading to the change with respect to the initial composition are outgassing, leakage and the permeation of hydrogen into the chamber produced by the thermal decomposition of the oil used as heat transfer fluid.

HITECO concept can operate in these conditions using the pumping system, and dragging the existing H_2 periodically. In any case, this vacuum level is not necessary to reduce thermal losses because the convection is avoided when the pressure level is below $5 \cdot 10^{-2}$ mbar having the same thermal losses. To operate in this pressure range produces similar thermal losses, allows an accurate control of the conditions in the chamber and, at the same time, reduces the cost and increases reliability of the system. As a consequence, and considering that HITECO is an open chamber concept in which is possible to produce vacuum, it is not necessary to operate in high vacuum conditions, obtaining comparable thermal results.

The repumping process described for the vacuum chamber can be done at any time during the lifetime of tube. According to the vacuum system used in the project and commercial characteristics of typical rotator and turbo pumps, the time required to achieve the initial conditions in a semicolector (75 meters) with a total volume of around 1000 liters is around 15 minutes. A critical parameter in the process is the conductance of the cross-section, which is defined as the resistance to flow in a pipeline because the difference of pressure in the ends. The elements determining the conductance in the vacuum chamber of the HITECO concept are the interanular area, the ceramic elements supporting the steel tube, and the flexible hose connecting the vacuum chamber and the pumps.

5.2. Analysis of alternatives and use of isolating gases

Considering the previous results using air in the vacuum chamber, it has been analyzed the operative alternatives throughout the conceptual development and initial testing of the concept, all of them aimed at reducing the pumping frequency and increasing its robustness. The most satisfactory alternative was the use of an isolating gas (typically Kr or Xe), which effectively reduces thermal losses at a particular pressure level with respect to the chamber completely filled with vacuum. The HITECO concept aims at working at pressure levels of around 20 mbar, with Kr as isolating gas in the chamber. Note that the reduced pumping frequency radically reduces the Operation & Maintenance cost of the plant.

Experimental and computational studies were carried out to evaluate thermal losses at pressure levels, temperatures of the absorber tube and compositions in the vacuum chamber, and the results obtained using in-house computational model are shown in Fig. 7. Note the significant impact of the isolating gas in the results, especially as pressure and temperature increase. At the target pressure level of 20 mbar, the use of Kr reduces thermal losses by around 80, 130 and 230 W/m at 400, 500 and 600ºC, which highlights the importance of such gasses especially at the higher temperature range considered in this study. The thermal losses are slightly higher than in current concepts working with isolating gas but the operations of maintenance are reduced and according the concept the chamber is always working in known conditions.

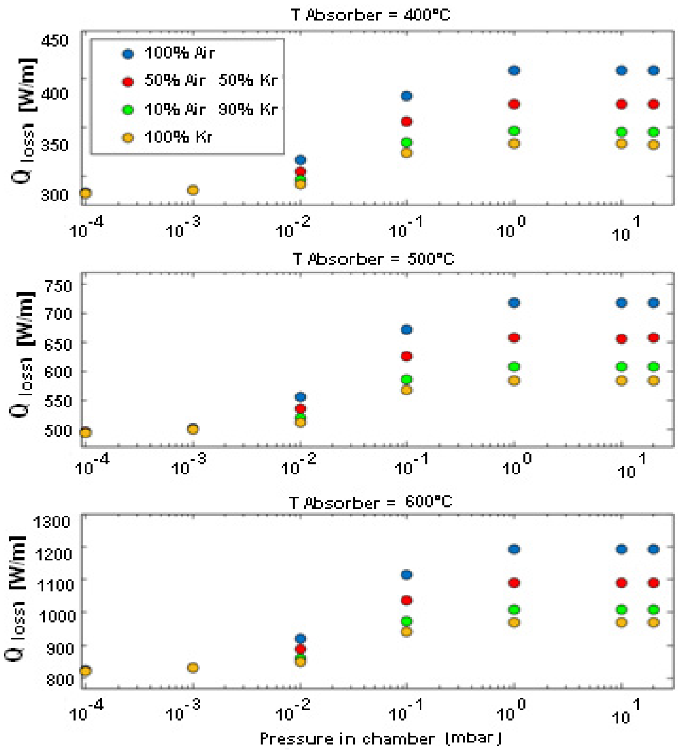

Fig. 7: Thermal losses by internal computational model at several temperatures, pressure levels and compositions in the vacuum chamber.

5.3. Operation & maintenance of field

Any operative situation describe previously can be easily managed to keep the conditions in the proper working range. The proposed system will be based in a mobile device that can access through the solar field (similar the cleaning device) operating in the collector that are out of operative range.

The connection with the solar collector will be done by a vacuum manifold located near the drive pylon, being the purpose of it to allow the repumping of HITECO tube the path for the supply of isolation gasses.

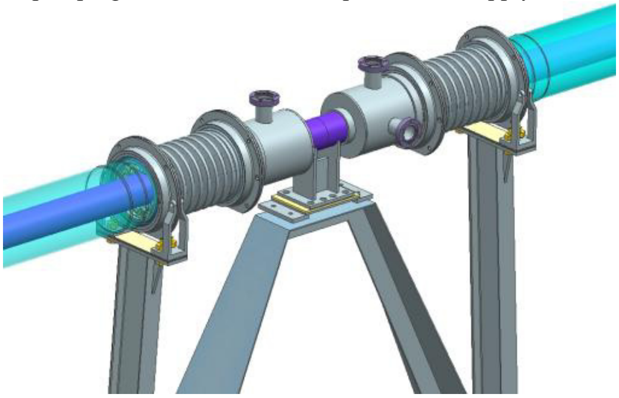

Fig. 8: Vacuum connection in solar collector

According the operative analysis done during the testing and validation process, it's expected to have a maximum of two repumping processes per year when the operation in field is carried with pressure of 20 mbar of Kr.

6. Conclusions

One of the key components in CSP technology is the absorber tube, which is designed to minimize convective heat losses by maintaining low pressure levels. Conventional collector designs are based on the concept of isolated vacuum chambers, where evacuation is performed during the manufacturing process, and pressure levels between 10^{-4} and 10^{-3} mbar are supposed to be maintained throughout the 20-25 years of expected life for the collector. However, a number of observations in field tests, such as the work by Price et al. [4], indicate that the conditions in the chamber vary, progressively leading to higher thermal losses. This is the result of several phenomena taking place in the vacuum chamber, such as outgassing, leakage, permeation or the increasingly high concentration of hydrogen produced by thermal degradation of the oil. Due to the fact that these chambers are isolated, currently it is not possible to determine the actual status of the chamber, or act on it to reduce thermal losses.

An alternative concept based on dynamic vacuum, in the context of the HITECO project [3] is described here. The project essentially proposes to use modular vacuum chambers, where the various sections are connected by means of sealing joints manufactured with an elastomeric material, and propose to monitor the status of the vacuum chamber continuously. These two ingredients allow not only a simpler and cheaper manufacturing process, but also the possibility to use vacuum pumps whenever necessary to reduce the pressure level and therefore thermal losses.

In this study it has been performed a comprehensive assessment of the various phenomena affecting the pressure level in the chamber, their respective contributions, as well as the development of a protocol for the initial installation of the vacuum chamber in a solar field. Additional experimental and computational data complement the conclusions stemming from the design, yielding a well-rounded collector which, with the adequate Operation & Maintenance strategy, significantly reduces the cost of electricity and increases reliability of conventional solar plants.

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