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Analysis of CSP Parabolic though Tube Receiver for Optimizing Damage

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ABSTRACT :

This project involves four principal milestones. The first milestone consists of analyzing all possible design related causes leading to HCE damage; mainly glass-to-metal seal breakage, HTF cracking, and shield diffusivity. The second milestone entangles some of the possible operational problems . The third milestone is devoted to a detailed, coupled numerical analysis of the effects of vacuum loss using ANSYS software. This later analysis is conducted in two main steps; first a CFD conjugate heat transfer analysis, followed by a Static Structural analysis. Finally, the fourth milestone involves a solution design suggestion to encounter the damage problem.The analysis conducted in this project proved our theory that when vacuum is lost in the annulus part, the glass casing of HCE breaks. Thus, the solution suggested in this project is the implementation of a dynamic vacuum design.

1.Introduction to CSP

Concentrated solar energy, normally referred to as CSP, systems square measure devices that generate solar energy obtained through changing daylight. These systems usually use mirrors, lenses or alternative reflective materials to concentrate the daylight, collected over the realm of the collector, onto a way smaller space.

1.1 Parabolic Trough Technology

Parabolic trough technology has many uses and applications depending on its operating temperature. As mentioned earlier, parabolic troughs are based on a line concentrating system, where a working fluid passes through a heat collector element, absorbs heat, and generates power. In fact, parabolic troughs are used in concentrated solar power plants for electricity production. The operating temperature of this latter application ranges from 300°C to 400°C. Whereas for industrial process heat (IPH) applications, the operating temperatures are 100°C to 250°C.

In this work, we are concerned with the first application only. To produce electricity through parabolic troughs, there are two possible steam power plant integration approaches. Either the parabolic troughs are directly related to the steam power plant through a Direct Steam Generation (DSG) system, or indirectly by heating a working fluid which then exchanges heat in aheat exchanger for steam generation, and thus power production.

1.2 Mirrors and Support Structure

Parabolic through mirror reflectors are made of ultra-clear tempered glass with a reflectivity up to 94.5% depending on the glass thickness and technology. The mirrors are coated with a silver reflective layer, followed by a copper layer and three other layers that guarantee durability, or coated by polished aluminum and metallized acrylic. The first coating is the best because it has a higher solar reflectance. The support structure for these reflectors is an essential aspect in a good performance of the entire plant. The structure has to be stiff and should be able to withstand deformations related to the weight of the reflectors, the wind, and the expansion of HCEs. Also, the structure should have an easiness to the one-axis tracking system that maximizes the total solar absorbance.

1.2.1 Heat Collector Element (HCE)

Heat collector elements or receiver tube is one of the most important components of a parabolic trough. HCEs are composed of an inner steel tube with a selective coating, enveloped in a glass tube, and vacuum between the two tubes. The HCEs are secured by glass-to-metal seals and metal bellows along the extremities as shown in Fig 5. The type of the seal and its characteristics is crucial in maintaining the necessary vacuum between the tubes and ensure a safe expansion. The vacuum in the HCEs is usually about 10-4 mbar. This vacuum is put in place mainly to reduce convection losses from the steel tube to the glass casing and exterior environment.

HCEs are about 4m long, the steel tube is usually 70mm in outer diameter and has a thickness of about 2mm. For the glass tube, its outer diameter is about 115mm with a wall thickness of 3 mm. Also, hydrogen absorber getters are put in place in the vacuum gap to maintain the required vacuum pressure.

More details about the geometry and materials characteristics of HCEs will be discussedthroughout this work .

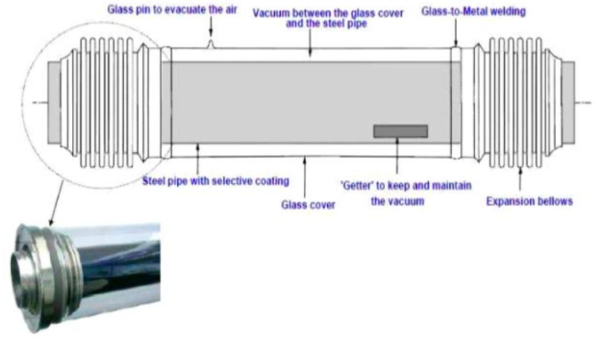


Figure 1: Heat Collector Element

2.LITERATURE REVIEW

1 Thermal Performance Enhancement Using Absorber Tube with Inner Helical Axial Fins in a Parabolic Trough Solar Collector. By Mohammad Zaboli et al 2021

In the present work, a parabolic trough solar (PTC) collector with inner helical axial fins as swirl generator or turbulator is considered and analyzed numerically. The three-dimensional numerical simulations have been done by finite volume method (FVM) using a commercial CFD code, ANSYS FLUENT 18.2. The spatial discretization of mass, momentum, energy equations, and turbulence kinetic energy has been obtained by a second-order upwind scheme. To compute gradients, Green-Gauss cell-based method has been employed. This work consists of two sections where, first, four various geometries are appraised, and in the following, the selected schematic of the collector from the previous part is selected, and four various pitches of inner helical fins including 250, 500, 750 and 1000 mm are studied. All the numerical results are obtained by utilizing the FVM. Results show that the thermal performance improvement by 23.1% could be achieved by using one of the proposed innovative parabolic trough solar collectors compare to the simple one. Additionally, the minimum and maximum thermal performance improvement (compare to the case without fins) belong to the case with P = 250 mm by 14.1% and, to the case with P = 1000 mm by 21.53%, respectively.

2 EXPERIMENTATION AND OPTIMIZATION OF GLASS-TO-METAL SEALS IN SOLAR RECEIVER TUBES by Ashutosh s singhare et al 2019

In parabolic trough solar power system solar receiver tube could be a key part to convert the solar energy into thermal energy. The residual stresses that are generated throughout the cooling method of the seal will decrease the seal strength and induce the breakage of the glass-to-metal sealing. The dependability of receiver tube considerably influence because of the residual stresses that are generated throughout the cooling method of glass-to-metal sealing. The failure or degradation of solar absorbent tubes is that the single largest value issue for current parabolic trough solar energy plant. To lower the seal failure likelihood, the stress distributions within the glass side are analyzed by using photo- elastic technique in agreement with the analytic answer approach.

3 Factors Affecting the Performance of Glass–Metal Seal of Solar Receiver Tubes: A Review By Vinod Kumar Verma B.Tripathi et al 2018

World is heading towards renewable sources of energy with increase in the population. Solar energy is one of the major renewable energy sources which has tremendous scope because of direct and large solar flux abundance, as well as large open fields to harness the direct sun rays. Generally solar energy is harnessed by PV panels and various kinds of concentrating type receivers. In the concentrating type solar receiver tubes, main cause of failure is leakage at the junction of glass to metal joint (seal) due to high difference in coefficient of thermal expansion of glass tube and steel bellows. These seals are also subjected to high residual stresses and repeated thermal cycling during its operation. For making glass to metal seal, various materials and procedures are under investigation to overcome this failure and increase the life and efficiency of tubes. The effects of various factors on the performance of glass–metal seal of solar receiver tubes were comprehensively reviewed throughout this article.

4 The calculation and analysis of glass-to-metal sealing stress in solar absorber tube by Dongqiang Lei et al 2010

This paper analyzes the effects of thickness and thermal expansion coefficients of both the glass and metal components of the HCE seal in stress distribution. Following an analytical study using the thin shell theory and the thermal stress theory, they have reached that the part of the seal that is under the most dangerous axial stress is near the sealing interface at the outer surface of the glass tube. This was also proved by the photoelastic technique and the tensile test. Thus, the analytical approach used in this paper proved to be accurate in analyzing the residual stresses developed in a glass-to-metal seal of an HCE.

5 Thermal modeling and simulation of parabolic trough receiver tubes by Markus Eck et al 2010

This paper analyzes and compares three different methods of HCE thermal simulation. The first approach is the analytical model, which consists of a linear set of equations that can be solved manually by defining a set of assumptions and boundary conditions. The assumptions are mainly that the inner boundary of the steel tube can be either wetted or un-wetted, and that the outer boundary of the steel tube can be either radiated or un-irradiated. This leads to four possible segments in the HCE: wetted and irradiated, wetted and un-irradiated, un-wetted and radiated, and un-wetted and un-radiated.

The second approach investigated in the paper is the Sandia model. This model consists of a thermal node network starting from the heat transfer fluid to the outer environment, where each node has a specific temperature value and is connected to the next node by one or more of the heat transfer mechanisms (convection, conduction, radiation). The third method is the finite element method model by ANSYS. The input solar radiation was in the form of a 2-D heat flux simulated by a raytracing model. In addition, specific fluid and material properties were considered. The finite element method turned out to be a good model for heat losses and temperature simulation.

3.Objective of problem

The present study deals with heat transfer within a pipe carrying water flow in a parabolic solar collector by ANSYS Fluent software. In fact, in the present model, there is a water-flow pipe that has been exposed to solar radiation. Behind the tube, there is a parabolic plate as the solar radiation absorber plate, which is responsible for absorbing the solar radiation energy and then reflecting it. This is the mechanism of a parabolic solar collector.

In this case, only a water flow pipe is modeled, such that the water pipe wall is divided into two upper and lower wall sections. The upper part of the wall is directly exposed to solar energy, while the lower part of the wall is influenced by reflective energy from the parabolic absorber plates of the collector. Two different constant heat fluxes applied on two walls.

4.Methodology

This project consists of two main parts.

The first step is setting and explaining the possible causes of HCE glass breakage. We divided these causes/problems in two main categories in this work. First, we will talk about design related possible causes of the glass casing crack, mainly glass-to-metal seal related problems, HTF cracking, glass permeation, and aluminum shield diffusivity. Second, we will discuss some operational problems that might lead to the glass breakage such as mass flow rates and vanes' opening.

As it will be demonstrated later, most of these possible problems lead to vacuum loss in the annulus part between the two tubes. The air leakage into the annulus part is the main cause of convection losses from the steel tube to the glass envelope, thus leading to high thermal transfer to the glass casing. Using a simulation analysis by a software called ANSYS, we will demonstrate the thermal transfer between the two tubes in the case of vacuum loss in the annulus zone. From this thermal analysis we will be able to simulate the exact amount of residual stress generated across the glass envelope. This residual stress will enable us to know if the glass will break or not, by comparing the analysis' results to the glass' yield stress. So, mainly the software analysis is by itself divided into two parts. First we will proceed by a conjugate heat transfer-CFD analysis (in fluent). Followed by a static structural analysis.

HCE Damage Analysis

4.1.1 Design Related Possible Causes

HCE glass breakage in CSP plant may be related to one or more of the following design problems. In fact, the cause of HCE damage may be because of a non-performant glass-to-metal seal, a phase or chemical change at the level of the HTF, unsuitable glass properties, or a nonefficient aluminum shield. These problems will be discussed in more details independently. However, the problem might be coming from a combination of two or more of these aspects. The rule that has to be put in place here is that, if at least one problem is observed then it can engender HCE damage.

- **4.1.2 Glass-to-metal Seal Breakage**

The best glass-to-metal seal designed so far for parabolic trough practices is constituted of a tubular metal ring embedded 2 to 3mm in the glass tube. This metal ring is constituted of a special alloy called Kovar, made of Nickel-Cobalt-Iron. This alloy is specially used in this application because of its similar thermal expansion coefficient to that of glass, about $3.3E^{\&'}K^{\&*}$.

Apart from the glass-to-metal seal, each HCE extremity is also composed of a metal folding below. This bellow accounts for the expansion difference between the steel tube and the glass envelope. As a matter of fact, the steel tube is confronted to higher temperatures since the HTF flows inside it. The temperature in the steel tube reaches 393℃, whereas the glass tube is only faced to solar radiation (in the case of a perfect vacuum). Thus, the bellow's role is to enable the steel tube to expand without harming the glass tube. It enables an expansion compensation between the glass pipe and the steel pipe. Fig 8 shows how the bellow and the glass-to-metal seal are included in the HCE.

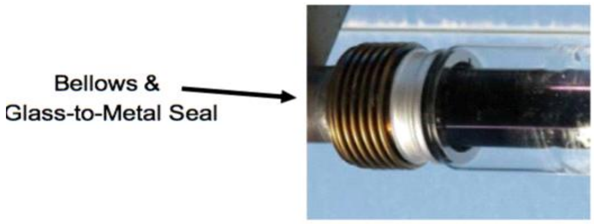


Figure: Glass-to-metal Seal

The main issue found in glass-to-metal seals is the residual stress produced during the cooling process of the glass or from temperature changes during operating .

- **4.1.4 Aluminum Shield Diffusivity**

The shield element is used in parabolic trough applications to protect the glass-to-metal seals at the extremities of the HCEs. As mentioned in previous parts, the glass-to-metal seal is the most fragile part of an HCE, because it is a connection of two different materials. The shield is put in place to disable mainly solar radiation and thus heat flux concentrated towards the glass-to-metal seal. The supplier company of the HCEs (Schott), also provides aluminum shields, and advices its buyers to buy their HCE products along with their shields This can pose a problem, in such a way that the shields used in csp 1 plant are not performant enough for this specific application. We believe that the shields used in CSP PLANT may be the reason of the glass breakage. The shield's used may have a high diffusivity of both solar radiation, and rain. The diffusivity of sun rays through the aluminum shield, and thus their penetration into the glass-to-metal seal heats up this part. The difference in expansion between the metal ring and the borosilicate glass leads to stress generation of the metal ring on the glass .

Also, in case of rain penetration, a thermal chock may occur at the level of the bellows. The temperatures in the bellows are very high due to conduction from the steel tube. Thus, few droplets of cold water deposited on the metal bellow leads to a thermal shock, and so different parts of the bellow expand differently. This expansion difference again, leads to stress generation and therefore causing the the bellow to crack. With the cracking of the bellow many problems are induced. Air can penetrate in both the annulus zone and the inside of the steel tube. As explained before, air leakage in the annulus part leads degradation of the cermet coating of the steel tube, and also enables convection losses to the glass casing (this will be proved in the software analysis part later in this chapter). The fact that air enters the steel tube also poses a serious problem. Air affects directly the flow of the HTF and also its eutectic phase. As discussed in the HTF cracking part of this chapter, the presence of molecular hydrogen leads to chemical reactions which affects fluid properties. Operational Possible Causes

Software Analysis of Vacuum Loss

As discussed in the previous analysis parts, most of these problems lead to a more narrowed and analyzable problem which is vacuum loss. Instead of analyzing each hypothesis at a time, we opted first to analyze for what is in common between all of them.

In this part, we will mainly show the steps followed for running the simulation in ANSYS, and the results we got. From the simulation's results we will be to check our theory that says when vacuum is lost, the glass casing breaks.

We particularly chose ANSYS because of it is a powerful simulation software that enables its users to run different kind of analyses and most importantly link them together. We were mainly interested in ANSYS Fluent, and ANSYS Mechanical,

5.2.1 Problem specifications

The objective of the simulation in ANSYS is to generate the stresses applied on the glass envelope when the vacuum is not maintained to the same characteristics as the first day in production. The causes of vacuum loss are discussed in the two precedent parts of the HCE damage analysis.

This part proves the theory that when vacuum is lost the glass envelope breaks. We proceeded in two steps in this analysis part:

- 1st step: conjugate heat transfer-CFD analysis using ANSYS Fluent
- 2rd step: Static Structural Analysis using ANSYS Mechanical

The following picture (Fig 9) shows the project schematics. In this interface we have the possibility to choose the analysis we want and also to couple our analyses by importing information from one analysis to another. The steps of each analysis are ordered in such a way that you can't move to the next step unless the preceding one is set or configured. In most cases, if there is a problem/error in the preceding setup the user can't proceed to the next one until the problem is fixed. Once the step is correctly configured a check mark automatically appears in the right hand side of the setup box.

The procedure for coupling our analyses was to first import the geometry from CFD analysis (Mécanique des fluides) to the static structural analysis' geometry box. We then updated the model or generate the mesh in the static structural analysis. However, before proceeding to the next step we had to re-enter our material properties in the Engineering Data box. This is due to the fact that the material properties' setting done in CFD analysis was at the level of the Setup (or Configuration) and we cannot import the Setup of CFD analysis to Engineering Data in structural analysis. Following that, we imported the Solution from CFD to the Setup in the Static Structural analysis. We also, configured this setup according to the results we are looking for. The final solution of this coupled analysis is thus found in the Results part of the Static Structural analysis.

4.2.2 Pre-Analysis and Start-up

- CFD Analysis: The HTF enters the steel pipe with a certain volume flow rate, and exits the pipe with a certain pressure as shown in Fig 10.

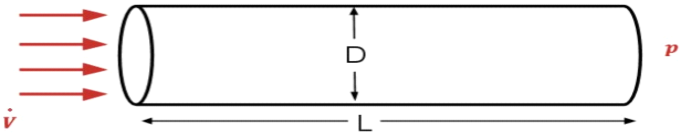


Figure 10: CFD Pre-Analysis

Heat transfer: Fig 11 shows the different types of heat transfer occurring between all the parts of the HCE.

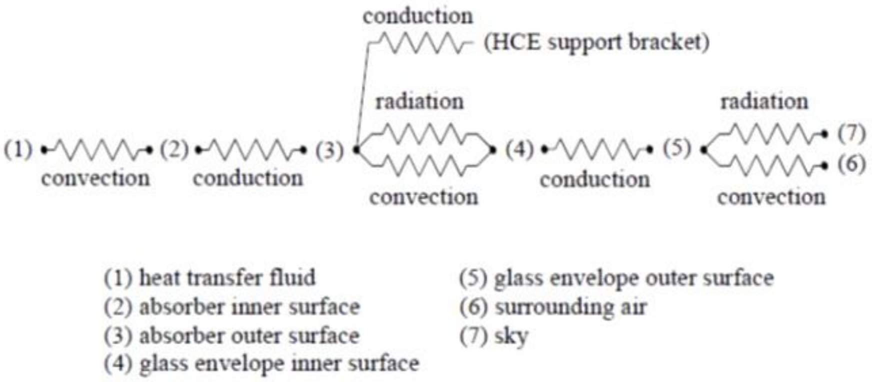


Figure 11: Heat Transfer Pre-Analysis

- **5.2.3 Geometry**
  - Conjugate heat transfer and CFD Analysis: in this first part we designed two concentric tubes according to the specifications shown in Table 1:

Table 1: Geometry Properties

Diameter/Tube	**Outer Diameter**	**Inner Diameter**	**Length**
Stainless Steel Tube	70mm	68mm	4061mm
Glass Tube	115mm	112mm	4061mm

  - Static Structural Analysis: the geometry is imported from CFD analysis

- **5.2.4 Mesh**

The mesh was done automatically by the software. As shown in Fig 12, the main element type used for discretization were hexahedrons. Tetrahedrons were also used in the two faces of the HTF flow domain.

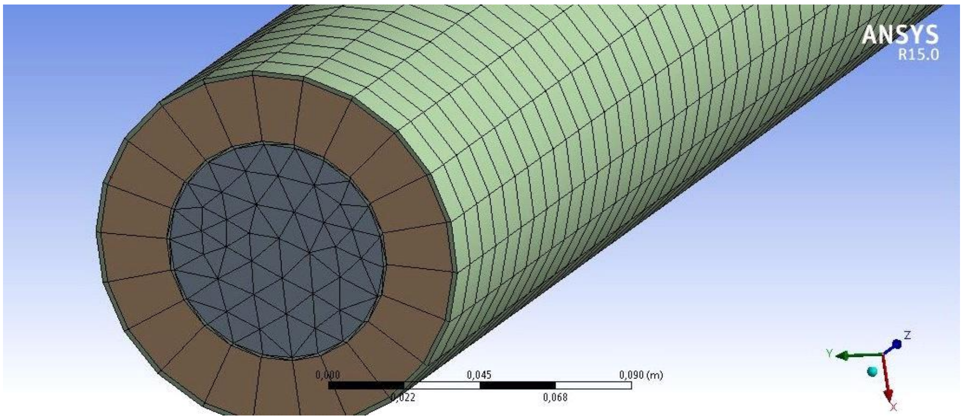


Figure 12: Mesh Model

The number of elements and nodes generated in the discretization of our design, their size and other mesh characteristics are shown in Fig 13.

Physics Setup

For conjugate heat transfer-CFD Analysis:

- General: the solver's type is left as it is set in default to pressure based, the velocity formulation is absolute, and time is fixed to steady.
- Model:
-

-Energy equation is turned on

-Viscous Model is set to k-epsilon with a standard model, and standard wall functions

Table 2: Material Properties

Material Properties	**Thermal Conductivity** $(W/m.\,K)$	**Density** $(Kg/m^{@})$	**Specific Heat** $(J/Kg.\,K)$	**Viscosity** $(Kg/m.\,s)$
Dowtherm A	**Piecewise-linear**	**Piecewise-linear**	**Piecewise-linear**	**Piecewise-linear**
	@285K⇒ 0,14	@285K⇒1065.9	@285⇒1550	@285⇒5520
	@483K⇒0.1083	@493⇒888.3	@493⇒2134	@493⇒340
	@563K⇒0.0795	@663⇒695	@663⇒2657	@663⇒130
	@668⇒0.0787	@668⇒687	@668⇒2678	@668⇒130
Stainless Steel DIN 1.4541	Constant 15	Constant 7.9	Constant 500	-
Borosilicate Glass	Constant 1.2	Constant 22.3	Constant 830	-
Air	Standard	Standard	Standard	Standard

- Cell Zone Conditions: in this setup, each zone of the geometry is assigned the necessary material.
- Boundary Conditions: Table 3 shows the boundary conditions used in this analysis.

Table 3: Boundary Condition Entries

Zone	**Boundary Conditions**
HTF inlet	Mass flow rate and fluid temperature
HTF outlet	Outflow condition
Glass pipe wall	No slip condition and heat flux taken from solar load tracing
Steel pipe	No slip condition and coupled thermal condition
Wall part glasspipe vacuum shadow	Coupled thermal condition
Wall part glasspipe vacuum	Coupled thermal condition

For Static Structural analysis: the results of the CFD analysis were imported in the physics setup part of the structural analysis. All we had to do was to define which result parts of the design should be imported. We selected two surfaces; the glass wall and the glass-vacuum shadow.

numerical Solution

Conjugate heat transfer-CFD analysis: before starting the calculation, we initialized the problem, which is basically telling the software from where it should start its calculations. The initialization was form HTF inlet. As a start we solved the problem with 200 iterations. Later on, the number of iterations will be changed using the method of solution convergence. The governing equations used in this analysis are as following .

-Continuity equation

$$\frac{\partial\rho}{\partial t} + \nabla.\,\rho V = 0$$

-Momentum conservation equation

$$\rho\frac{Du}{Dt} = \frac{\partial(\rho u)}{\partial t} + +\nabla.\quad \rho u V$$

-Energy equation

$$\rho\frac{De}{Dt} = \frac{\partial(\rho e)}{\partial t} + +\nabla.\quad \rho e V$$

• Static Structural analysis: in this analysis, the stress option was used. The part of the geometry selected for stress generation is the glass tube only.

- **5.3.1 Numerical Results**
- Conjugate heat transfer-CFD analysis: in order to perceive the temperature contour, we first designated a plane that takes into consideration all the parts of our design. This plane is then fed to the contour to display the results. Fig 15 shows the temperature contour of the glass casing in Kelvin.

The maximum temperature generated on the glass envelope is about 405℃.

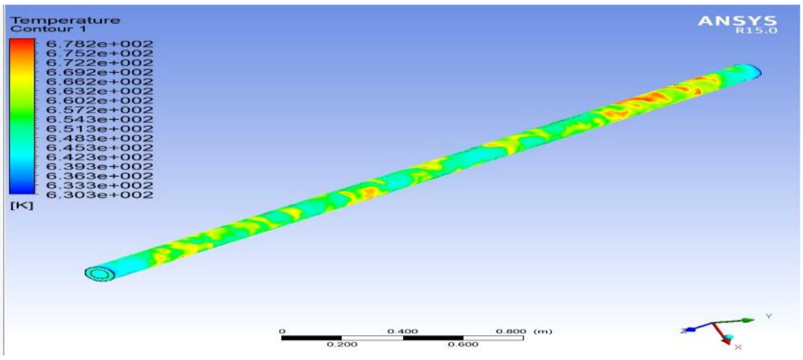
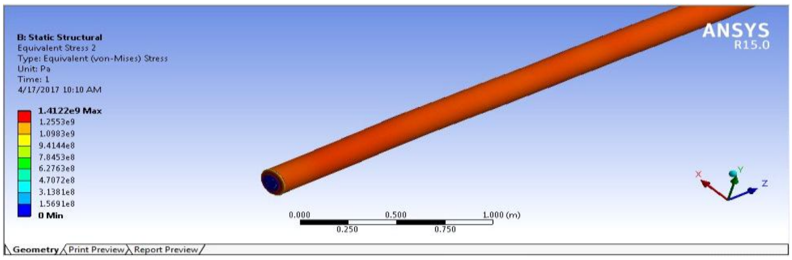


Figure 15: Conjugate Heat Transfer-CFD Results

Structural analysis: The following picture (Fig 16) shows the stress generated in the glass envelope due to thermal gradients.



Static Structural Results

Interpretation:

According to the simulation conducted in ANSYS software, the thermal stress developed in the glass casing reaches about 1400 MPa. Since the tensile strength of borosilicate glass is 280 MPa, we can conclude that the thermal stress generated due to vacuum loss exceeds the tensile strength of glass, and thus leads to its breakage.

- **Solution Design**

As proved in the previous chapter, losing vacuum in the annulus part leads to the glass envelope's breakage. The solution design suggested in this project is to implement a dynamic vacuum system that will maintain the vacuum necessary for an efficient operation of HCEs.

The current design consists of making the vacuum only at the manufacturing process. For maintenance, a getter system inside the vacuum zone is used. Its purpose is to absorb the gases available in the vacuum. However, this system works only for low gas amounts, and is not performant in case of serious leakage.

Our solution provides a more efficient and effective way for vacuum maintenance. We suggest that HCEs should consist of continuous open chambers that will enable air elimination through the use of a pumping system. The pumping system would be related to a very sensitive pressure probe that ignites the pump to work in case of high pressure values, mainly beyond $10^{\&@} mbar$.

Conclusion

This work consisted of a theoretical and numerical analysis of HCE damage, in addition to a solution design suggestion. The analysis part was mainly divided into three subparts. Design related problems were analyzed, mainly glass-to-metal seal breakage, HTF cracking, aluminum shield diffusivity. Also, possible operational problems were analyzed, mainly mass flow rate at winter. Followed by a software analysis of vacuum loss. The simulation conducted in ANSYS software is a coupled analysis, and is divided into two main parts. First, a conjugate heat transferCFD analysis. Followed by a structural analysis. The results obtained in this analysis were the temperature distribution and its resulted thermal stress across the glass tube. Via this simulation we were able to prove that when vacuum is lost, the glass casing breaks. So, our solution design is to implement a dynamic vacuum system that will maintain the required vacuum pressure for in the annulus zone, avoid the HCE damage, and thus MAY improve the overall efficiency of CSP thought power plant.

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