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Optimization of Glass-to-Metal Sealsin Solar Receiver Tubes

[#1]Akash Y Khaladkar, [#2]Dr S V Kshirsagar

[1]akashkhaladkar47@gmail.com
[2]svkshirsagar@aissmscoe.com

[#12]Department of Mechanical Engineering, Savitribai Phule Pune University,
AISSMS's College of Engineering , Kennedy road Shivajinagar Pune-01.

ABSTRACT

The solar receiver tube is a key component to convert the solar energy into thermal energy in parabolic trough solar power system. The residual stresses that are generated during the cooling process of the seal can decrease the seal strength and induce the breakage of the glass-to-metal sealing. The residual stresses which are generated during the cooling process of glass-to-metal sealing significantly influence the reliability of receiver tube. The failure or degradation of solar absorber tubes is the single largest cost factor for current parabolic trough solar power plant. In order to lower the seal failure probability, the effects of material properties of glass-to-metal seals on the residual stresses are analyzed using finite element method. Moreover, effects of the metal tube and the glass tube length on the residual stress will also be analyzed. The stress distributions in the glass side are analyzed by the finite element method, in agreement with the ones to calculate by analytic solution approach & will be measured experimentally by using various techniques, such as X-ray measurement or photo-elastic techniques.

***Keywords*— Solar Absorber Tube, Glass-To-Metal Seal, Residual Stress, X-ray measurement, photo-elastic technique**

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I. INTRODUCTION

A parabolic trough solar receiver is one of the most important elements in the solar thermal power system for converting the solar energy into thermal energy. The receiver typically consists of a metal pipe with a solar selective coating and an evacuated glass tube. The receiver tube incorporates glass-metal transitional elements and metal bellows to achieve the necessary vacuum-tight enclosure and to accommodate for thermal expansion difference between the metal pipe and the glass envelope, where in the central metal pipe and the glass-metal transitional element are connected with each other by means of bellows so that they can move relative to each other in a longitudinal direction[1]. The vacuum enclosure serves primarily to significantly reduce heat losses at high operating temperatures and to protect the solar selective absorber surface from oxidation.Glass-to-metal seals are widely used in the solar receiver tube that is a key component in the parabolic trough solar thermal power system[3]. The receiver tube consists of a central metal pipe with a cermet solar-selective absorber surface, surrounded by an evacuated glass envelope. Failure or degradation of the receiver, which causes vacuum loss, fracture of glass tube and solar selective coating degradation, is the single largest cost factor for present current and future solar power plant.Breakage of glass-to-metal sealing is main cause for damages of receivers. The problems of sealing are adhesion and stress. The adhesion is only a firm layer of metal oxide that is soluble in both metal and glass, and is the means of obtaining adherence. The reliability of the glass-metal bond is determined by the thickness of the oxide film, the uniformity of the layer and the oxide species. Pre-oxidation is a common technique to improve the chemical bonding. Through exact temperature and process control, a good glass-to-metal seal can be obtained. So adhesion problem is ignored.The residual stresses that are inevitable in the glass-to-metal seal as a result of the difference in thermal contraction of the two components from the sealing temperature down to the room temperature[2]. The stress can significantly decrease the seal strength and influence the reliability of the receiver tube. The temperature changes during operation can also induce thermal stress that is an overlapped stress in the glass-to-metal seal. Therefore, it is necessary to evaluate the magnitude and distribution of residual stresses and to explore whether the stresses are great enough to cause cracks. To ensure vacuum stability over the whole lifetime of the receiver tube, a glass-to-metal seal with high mechanical strength and temperature resistance is needed. This implies a stress-free bonding between the metal part and the glass part.

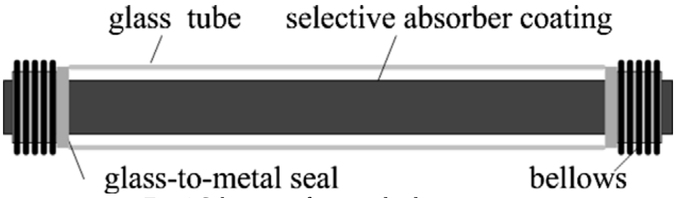

Fig. 1.Schematic of a typical solar receiver

I. PROBLEM STATEMENT

Glass-to-metal seals are widely used in the solar receiver tube that is a key component in the parabolic trough solar thermal power system. The receiver tube consists of a central metal pipe with a cermet solar-selective absorber surface, surrounded by an evacuated glass envelope. It incorporates glass–metal transitional elements and metal bellows to achieve the necessary vacuum-tight enclosure and to accommodate for thermal expansion difference between the metal pipe and the glass envelope [4]. Breakage of glass-to-metal sealing is main cause for damages of receivers in existing power plants. The residual stresses that are generated during the cooling process of the seal can decrease the seal strength and induce the breakage of the glass-to-metal sealing. The failure or degradation of solar absorber tubes is the single largest cost factor for current parabolic trough solar power plant [2]. In order to lower the seal failure probability, the effects of geometry and material properties of glass-to-metal seals on the residual stresses will be analyzed using finite element method.

II. SCOPE

Parabolic trough technology the first choice for large-scale solar power generation, Concentrated Solar Power (CSP) technology uses energy from the sun to generate heat, which is used in steam cycles to produce electricity. The technology is particularly efficient in regions with high direct solar irradiation, encompassing the earth's sunbelt on both sides of the equator. CSP plants are used in a similar manner like conventional steam power plants. The key difference is that CSP plants use emission-free, clean solar radiation to produce heat instead of fossil or nuclear fuels.

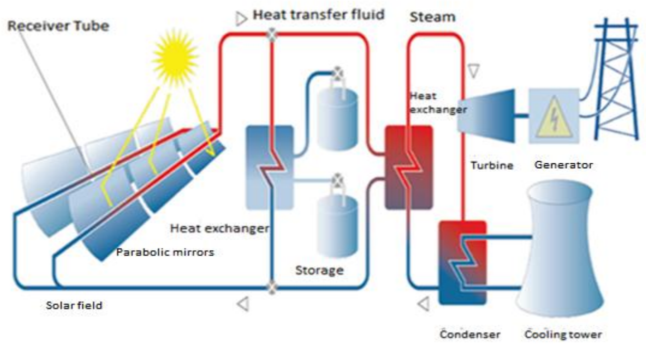

Fig. 2.Working principle of parabolic trough power plants

Amongst all CSP technologies, the parabolic trough technology has the longest commercial track record. Parabolic trough power plants are suitable for large-scale electrical output and can replace conventional thermal power plants without any qualitative changes in the electricity grid structure. Due to the option of thermal storage or hybridization, the turbines of CSP plants can also produce power in low solar radiation periods and at night, delivering power reliably.

III. LITERATURE REVIEW

D.Q. Lei, Z.F. Wang, Z.J. Wang (2013) [1] analyzed the solar receiver tube is a key component to convert the solar energy into thermal energy in parabolic trough solar power system. The residual stresses which are generated during the cooling process of glass-to-metal sealing significantly influence the reliability of receiver tube. In order to lower the seal failure probability, effects of geometry and material properties of glass-to-metal seals on residual stress were analyzed by using finite element method in this paper. The residual stresses distribution in glass-to-metal seals was simulated. The effects of the material properties of stainless steel 304, stainless steel 430, Kovar on the sealing residual stress can be presented. Although each of these different sealing material combinations can have enough sealing strength, the glass-to-metal seals with larger tensile stresses can cause the failure of the receiver tube were analyzed in this paper. The stress distributions in the glass side analyzed by FEM were in agreement with the ones calculated by analytic solution approach. The X-ray measurement results also proved the validation of the finite element method. The dangerous tensile stresses mainly occur at the glass-metal interface. The results of this study have important implications on the optimization of seal configuration in the solar receiver tubes

Dongqiang Lei, Zhifeng Wang, Jian Li (May 2009) [2] analyzed how the thickness of glass tube, thickness of metal ring, and thermal expansion coefficient affect the residual stress distribution. According to the thin shell theory and thermal stress theory, this paper theoretically analyzes the glass-to-metal sealing residual stress and obtains the analytic solution for the tubular sealing structure in the solar absorber tube. The photo elastic technique is used to measure the residual stress, and the tensile test is used to obtain the point of the most dangerous stress and the tensile strength for the sealed specimens. The calculated results agree well with the test results. The theoretical analysis is proved feasible and helpful to analyze the residual stress of glass-to-metal seals in the HCE and optimizes the sealing structure.

Dongqiang Lei, Zhifeng Wang, Jian Li (Nov 2009) [3]analyzed the residual stresses distribution in glass-to metal seals with tubular geometry is simulated using ANSYS finite element software and measured using photo-elastic technique. The dangerous tensile stresses occur not only at the glass–metal interface but also on the outer surface of glass tube near the sealing area. When the depth of metal embedded into glass increases, the magnitude of residual stress decreases and the sealing strength will increase. This tensile strength of glass-to-metal joint is tested in thematerial tensile testing machine. The simulation results agree with the measurement results, and the simulation method was proved feasible to analyze the residual stress of glass-to-metal seals employed in solar absorber receivers.

N.S. Rossini, M. Dassisti,K.Y.Benyounis, A.G.Olabi [4]analyzed the non-destructive residual stresses measurement methods have the obvious advantage of specimen preservation, and they are particularly useful for production quality control and for measurement of valuable specimens. However, these methods commonly require detailed calibrations on representative specimen material to give required computational data. The diffraction methods such as X-ray and neutron diffraction can be applied for the polycrystalline and fine grained materials as well as metallic or ceramic. The advantage of the neutron diffraction method in comparison with the X-ray technique is its lager penetration depth as X-ray method is limited for the measurement of residual stresses on the surface of materials. However, the relative cost of application of neutron diffraction method, is much higher, mainly because of the equipment cost and it is not recommended to be used for routine process quality control in engineering applications.

Dongqiang Lei, Zhifeng Wang, Jian Li(May 2012) [5]analyzed the sealing of a kovar alloy and a borosilicate glass developed for matched glass to metal seals in solar receiver tubes. High-frequency induction heating is used to seal the glass to the kovar with precise control of the sealing temperature in a highly automated process. The kovar pre-oxidization rate was measured at a number of controlled temperatures for various times.The pre-oxidation of the kovar and the sealing process were optimized using a series of tests to measure the vacuum tightness, sealing strength, seal interface microstructure and thermal shock. The glass-to-metal seals have good vacuum performance and sealing strength to meet the requirements of parabolic trough receiver tubes.

Fuqiang Wanga, Yong Shuai, Yuan Yuan, Bin Liu [6]analyzed the effects of material selection on the thermal stresses of tube receiver under concentrated solar irradiation are investigated by numerical analyses. Four different materials of tube receiver are employed for the numerical analyses. In this study, the thermal stress analyses of tube receiver under concentrated solar irradiation condition using variousmaterials are carried out.

V.THE STRESS ANALYSIS OF SEAL

The key work is to reduce the residual sealing stress in the structural design of glass-to-metal seal. Apart from the sealing procedure, the strength of glass-to-metal sealing strongly depends on the four main parameters: the coefficient of thermal expansion , thermal conductivity, Young's modulus, and sealing structure parameter. The sealing structure is generally tubular seal that the edge of the metal ring is embedded into glass tube in the HCE. In order to obtain reliable sealing, we can either match the two coefficients of thermal expansion in order to avoid the stresses in the seals, or just limit the stresses to some values that are not dangerous for the integrity of the seal. According to the current technology, it can be divided between matched sealing and unmatched sealing.

In matched seals the thermal expansion coefficients of both components are similar at least in the temperature range between the strain point of the glass and room temperature. Above the strain point stresses can be relaxed by viscous flow. Below the strain point no stress relief takes place and stresses, owing to differential expansion of the two joined materials, become permanent. The stress σ, generated by the temperature change, ΔT, and the difference of the thermal expansion coefficients, $\Delta\alpha$, between the glass and the metal can be written as

$$\sigma = -A\,(\Delta\alpha\Delta T)$$

Where A is, in general, a position (x, y, z) dependent term involving the elastic modulus, E , and Poisson's ratio, μ, of both components. When the geometry of the glass to metal sealing is simple, e.g. a glass rod and a metal rod are fixed at one endand are restrained to move together at their other end. When they are heated up to a same temperature, it can be obtained

$$A = \frac{E_g . E_m}{E_g + E_m}$$

Where E_g and E_m generally change very little as the materials change. To withstand greater changes in temperature, hard glass ($\alpha \leq 5\times$10-6 /K, e.g. borosilicate glass) is needed for the receiver tube. The tensile strength of borosilicate glass is generally 40-120MPa. Therefore, in order to ensure that the stress level is in the safe range ($\sigma \leq$ 40MPa), the mismatch of the thermal expansion coefficients should not exceed the value given in equation as follows

$$|\alpha_m - \alpha_g|\Delta T \leq 7.5 \times 10^{-4}$$

The matched sealing then gives much lower residual stresses in the glass to metal seal than the tensile strength of the glass itself. However, this choice would lead to higher costs and pretty high difficulties for the suppliers in the world to match the highly dedicated glass requirements geometrical and water resistance.

The unmatched seal are based either on the fact that the stresses developed in the glass are relieved by plastic or elastic deformation in the metal or on the fact that the developed stresses are only compression. The unmatched seal used in current designs is known as a Housekeeper seal which consists of a thin metal with blade like edges inserted into the glass to form the junction. The unmatched stainless steel-Pyrex glass seals were used in the original Luz receiver tubes which experienced high failure rates approximately 4–5% per year. Stress analysis has indicated that the high stresses resulted from differential expansion between the metal and the glass when solar flux is incident on the seal areas is the primary cause of this failure.

A Design

The manufacture of receiver tube is constrained by the reliability of glass-to-metal seals. The specimen comprises of a metal ring and a glass tube. The seal configuration used in solar receiver tube is a tubular seal, of which the edge of the metal ring is embedded into the glass wall. In order to obtain reliable seals, a kind of borosilicate glass with high optical transmittance is chosen in the experiments.

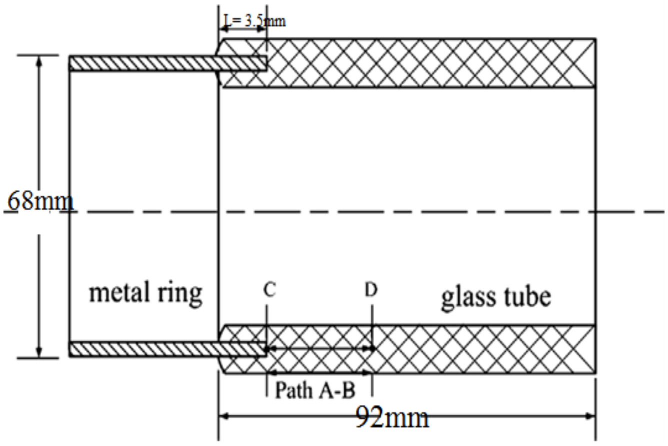

Fig. 3.Diagram of tubular seal

The glass tube has an outer diameter of 70 mm, a wall thickness of 3 mm, and a length of 113mm. The metal ring is made of the stainless steel 304 that has similar thermal expansion coefficient with the borosilicate glass. The metal ring has an outer diameter of 68 mm, a wall thickness of 1 mm and a length of 24mm. L designates the depth of metal ring embedded into glass. The diagram of tubular seal is shown in fig.3.

B Stress Analysis of Sealing Structure

In order to analyze the main problems and obtain the basic rules, a satisfactory approximate theory can be developed by making the following assumptions

i. The theory of thin shell can be applied to the analysis of sealing stress. The thickness of glass tube is far less than its radius, so this assumption is rational.
ii. The transient stress which caused by the uneven distribution of temperature in the sealed element is not considered in the calculation.
iii. The CTE of metal is assumed to be bigger than that of the glass, αm>αg It is impossible that the coefficients of expansion of metal and glass are the same over the whole temperature range from room temperature up to the transition point.

Through the assumptions, the structure of glass-to-metal seal is simplified as the diagram shown in Fig.4. According to the theory of thin shell and thermal stress theory, the contraction distortion of metal ring is larger than that of glass in the radial direction when the element is cooled from sealing temperature to ambient temperature. Both the glass tube and the metal ring are subject to the action of bending moments M (Nm/m) and shearing forces P (N/m) by contrary directions. The glass tube and the metal ring should meet the displacement and turn-angle displacement compatibility equation

$$\Delta_m^P - \Delta_m^M + \Delta_g^P + \Delta_m^M = \Delta \quad (1)$$

$$\theta_m^P - \theta_m^M = \theta_g^P + \theta_g^M$$

where, $\Delta_m^P = PK_m$,which denotes the radial displacement of metal ring caused by the forces P; $\Delta_g^P = PK_g$,which denotes the radial displacement of glass tube caused by the forces P; $\Delta_m^M = MK_m$,which denotes the radial displacement of metal ring caused by the moment M;$\Delta_g^M = MK_g$,which denotes the radial displacement of glass tube caused by the moment M; $\theta_m^P = PK'_m$,which denotes the turn-angle displacement of metal ring caused by the forces P; $\theta_g^P = PK'_g$, which denotes the turn-angle displacement of glass tube caused by the forces P; $\theta_m^M = MK''_m$, which denotes the turn-angle displacement of metal ring caused by the moment M; $\theta_g^M = MK''_g$, which denotes the turn-angle displacement of glass tube caused by the moment M.

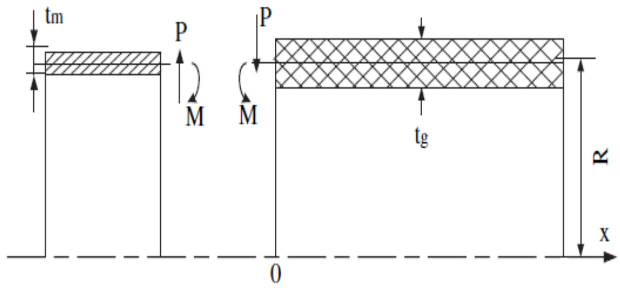

Fig. 4.Structure of the glass-to-metal seal

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; ; ;

$$K''_g = \frac{1}{(\beta_g . D_g)}; \ \beta = \left[\frac{3(1-\mu^2)}{t^2.R^2}\right]^{0.25}; D = \frac{E \ t^3}{12(1-\mu^2)}$$

Where, K_m , K'_m and K''_m denote the flexibility factors of metal ring, K_g , K''_g and K''_g , the flexibility factor of glass tube, D the flexural rigidity of material, R the radius of the middle plane in glass tube. t, α, μ and E respectively denotes the thickness, CTE, Poison' ratio and Young's modulus.

When the sealed elements are annealed, the glass can relieve internal stresses generated not only by the difference of CTEs of glass and metal but also by the sealing geometry. When the temperature is below the transition point (T_g), it retain the thermal stresses which will be permanent.

Where,$\Delta = (\alpha_m - \alpha_g)\,\Delta T\,R$. D is the radial displacement difference between glass tube and metal ring caused by the different CTEs from transition point to room temperature. Substituting these values in Eq.(1), we obtain

$$P = \frac{(\alpha_m - \alpha_g)\Delta T.R}{\left[(K_m + K_g) - \frac{(K'_m - K'_g)^2}{(K''_m + K''_g)}\right]}$$

$$M = \frac{K'_m - K'_g}{K''_m + K''_g}.P$$

According to the expression P and M, we can obtain the analytic solutions are shown as following equations

$$\sigma_{xg} = \pm\frac{6}{t_{g,\beta}^2}.e^{-\beta x}\left[(\beta M + P) + \beta M \ \cos\beta x\right] \qquad + \frac{t_m^2 E_m E_g \Delta t}{t_g(t_m E_m}$$

$$\sigma_{\theta g} = -\frac{2R\beta}{t_g}e^{-\beta x}\left[(\beta M + P)\cos\beta x - \beta M \sin\beta x\right] \quad (3)$$

$$\tau_{xrg} = -\frac{1}{t_g} e^{-\beta x}[P\cos\beta x - (P+2\beta M)\sin\beta x] \qquad (4)$$

Where, σ_{xg}, $\sigma_{\theta g}$, τ_{xrg} and denotes respectively the axial stress, circumferential stress and tangential stress on the glass tube. R , t , α, μ , E , D , x and β respectively denotes the radius of the middle plane, the thickness of tube, CTE, Poison' ratio, Young's modulus, the flexural rigidity of material, distance from the interface and the flexibility factors.

C Numerical results

In order to evaluate the glass-to-metal sealing stresses, someexamples are calculated with the above equations.The glasstube used in the experiments is a kind of borosilicate glass, whoseCTE is 4.8 10^{-6}/ (20–450), the thickness t_g= 3 mm and theouter diameter is 104 mm. The metal ring is a Fe–Ni–Co alloy namedKovar, whose CTE is 5.0 10^{-6}/),(20–450), and the thicknesst_m=1mm. The transition temperature (T_g) of this glass is 430 . It is seen that σ are always compressive stresses and τ are very small stresses on the glass tube, but axial stresses $\sigma_{xg}$are tensile on the outer surface of the glass tube while compressive on the inner surface.

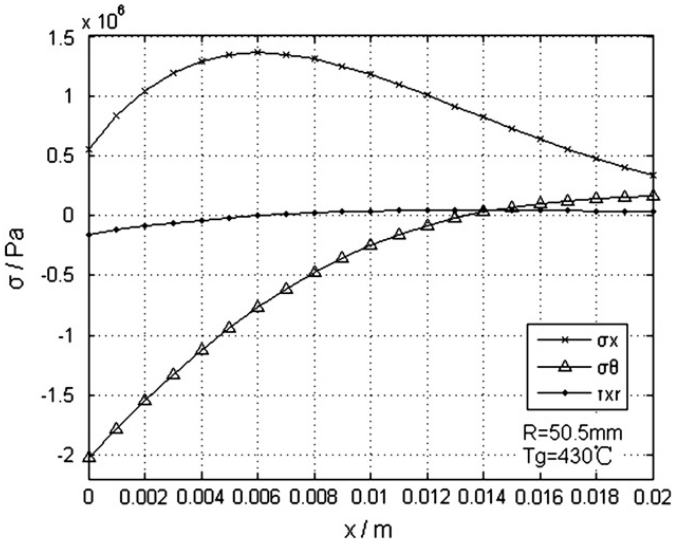

Fig. 5.Distribution of stresses on the glass tube [2]

According to the Equation (2), (3) and (4), the results obtained aregraphically represented for 0≤ x ≤0.02 m in above graph.

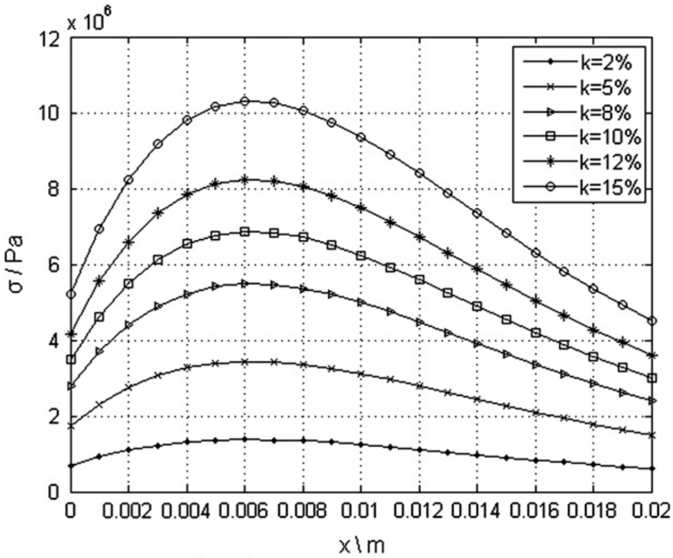

Fig. 6.Effect of the CET on the axial stresses [2]

We assume that the material of themetal is still Kovar and the CTE of the glass changes. The functionsσ_{xg} and k are represented graphically in Fig. 6. We obtain at x=5.5 mm the maximum axial stress σ_{xg} =1.4 MPa and at x = 0mm, we obtain the maximum circumference stress.

Where,

$$k = \frac{|\alpha_m - \alpha_g|}{\alpha_m}$$

V. MODELING STRATEGY

Due to axial symmetry, this tubular sealing structure was modeled by the 2-D thermal-structure coupled-field elements in the ANSYS program. The 2-D modeling for the simulation of metal-to-glass sealing was established, as shown in Fig. 7. The area near the glass-to-metal joint was meshed with 3000 nodes to obtain reasonably good results.

The path C-D is pre-defined in the model to analyze the stress distribution along the path.The relevant material properties include Young's modulus (E), Poisson ratio (μ), thermal conductivity (λ), specific heat (c), and thermal expansion coefficient (α).

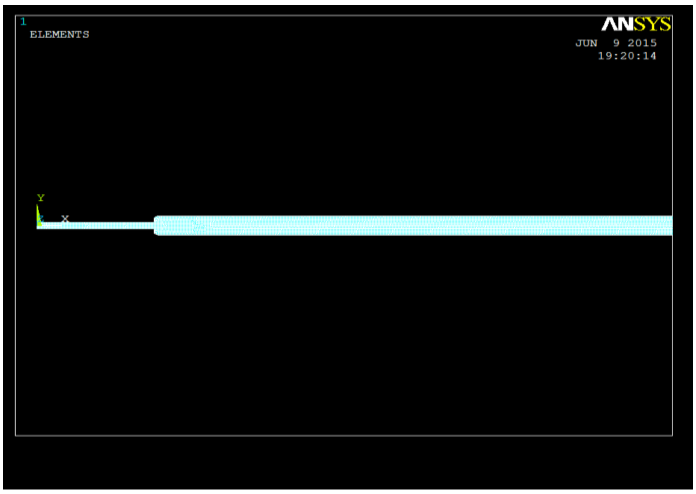

Fig. 7.A part of meshed FEA model

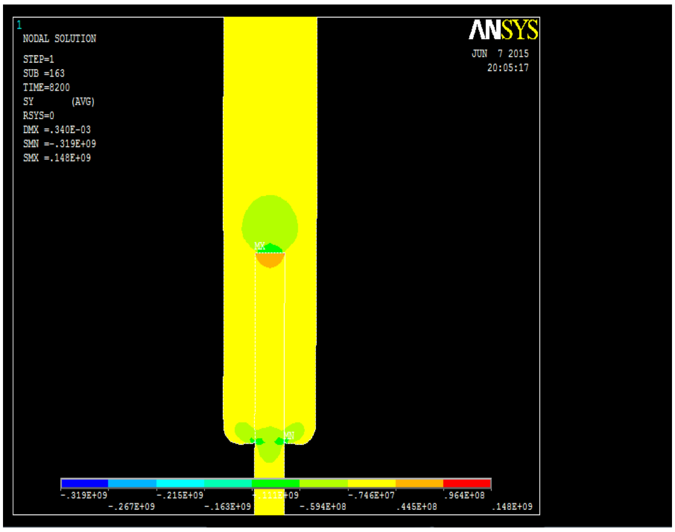

Fig. 8.Distribution of axial stresses

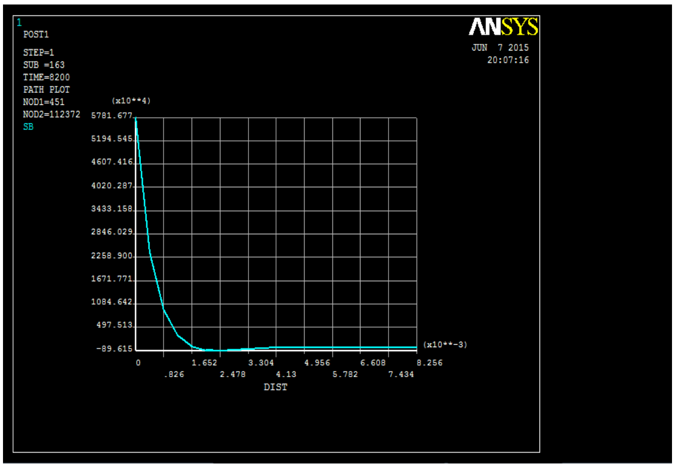

Fig.9.Distribution of axial stresses along the path of C–D

The maximum axial tress happens at the end of glass–metal interface as can be seen in Fig. 9 ,σ_{xg}=96.4 Mpa.The stress concentration is near the area of the glass–metal interface.

VI RESULT

Distance from interface (x) mm	Axial stress analytically calculated σ_{xg} Mpa	Axial stress using Ansys 14 σ_{xg}Mpa
0	69.30	59.46
3.5	82.01	44.56
5	83.46	96.4

Above table shows the axial stress distribution of glass-to-metal seal of Stainless steel 304 and Borosilicate glass at various point.The axial stresses are tensile on the outer surface of the glass tube and compressive on the inner surface. Since the glass is fragilematerial and its tensile strength is far less than the compressivestrength, the residual tensile stress is the most dangerous on theglass tube. The dangerous tensile stresses happen not only in thevicinity of the glass–metal interface but also on the outer surfaceof the glass tube, referring to Fig.8.

VII. CONCLUSIONS

This paper reports an evaluation of the residual stresses distribution in glass-to-metal seals with tubular geometry which is simulated using ANSYS 14 finite element software. According to the thin shell theory and thermal stress theory, this paper also analyzes the glass-to-metal sealing residual stress theoretically and obtains the analytic solution for the tubular sealing structure in the solar absorber tube. The simulation results agree with the theoretical results. The following conclusions can be reached:

I. The dangerous stress concentration generally occurs in thevicinity of the glass–metal interface. The place near the sealedarea should be protected from heat shock and non-uniform temperaturedistributions that occur due to hot spots created by theconcentrated solar radiation.

II. It is seen that when k is increased, increase greatly. Theresults show that the difference of CTE for the glass and the metal isthe principal factor affecting the magnitude of residual stress.

In this paper we obtain the result for Stainless steel 304 and Borosilicate glass which gives residual tensile stress σ_{xg}= 96.4 Mpa, which is dangerous to solar tube .So we will check another material Molybdenum (Mo-wire) having thermal expansion coefficient5.1 × 10^{-6}/ ℃ (93 ℃) with Borosilicate glass for optimizing the glass-to-metal seal in solar receiver tube.

ACKNOWLEDGMENT

The present study has been carried out in order to find out residual stress in receiver tube at different point.

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REFERENCES

[1] D.Q. Lei, Z.F. Wang, Z.J. Wang., 1991, “Effects of geometry and material properties on the residual Stress of glass-to-metal seals in solar receiver tubes”, Solar PACES 2013.

[2] Lei DQ, Wang ZF, Li J. “The calculation and analysis of glass-to-metal sealing stress in solar absorber tube”, Renewable Energy 2010; 35(2):405-11.

[3] Lei DQ, Wang ZF, Li J. “The analysis of residual stress in glass-to-metal seals for solar receiver tube”. Materials & Design 2010, 31(4): 1813- 1820.

[4] N.S. Rossini, M. Dassisti , K.Y. Benyounis, A.G. Olabi, “Methods of measuring residual stresses in components”, Materials and Design 35 (2012) 572–588.

[5] Lei DQ, Wang ZF, Li J. “Experimental study of glass to metal seals for parabolic trough receivers”, Renewable Energy 48 (2012) 85-91.

[6] Fuqiang Wanga, Yong Shuai, Yuan Yuan, Bin Liu. “Effects of material selection on the thermal stresses

of tube receiver under concentrated solar irradiation" ,Materials and Design 33 (2012) 284–291.

[7] H. Aben, L.Ainola, J.Anton "Integrated photoelasticity for nondestructive residual stress measurement in glass", Optics and Lasers in Engineering 33 (2000) 49-64.

[8] G. Leichtfried, G. Thurner, R. Weirather "Molybdenum alloys for glass-to-metal seals" , International Journal of Refractory Metals & Hard Materials 16 (1998) 13-22.

[9] A.S.Pidaparthi , N.R.Prasad "India's first solar thermal parabolic trough pilot power plant" , Energy Procedia 49 (2014) 1840 – 1847.

[10] D.Yogi Goswami Yuwen Zhao "Solar Energy and Human Settlement",Proceedings of ISES World Congress 2007.

