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A Computer Design Tool for Ceramic Receivers

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Abstract. Gen3 solar receivers and other components will experience a combination of high temperatures and high stress caused by thermal stress and internal pressure. Under these conditions metallic components, even those manufactured from nickel-based superalloys, have poor reliability. Engineering ceramics could be a solution, as these materials have excellent high temperature strength. However, accurately assessing the reliability of a ceramic component operating in these conditions requires an entirely different approach compared to metallic materials. This paper describes the implementation of statistical models for evaluating the reliability of high temperature ceramic components in srlife – an open-source software package for estimating the life of high temperature concentrating solar power equipment. This new capability allows users to make fair comparisons between competing metallic and ceramic component designs and to accurately assess the plant efficiency and economics of ceramic solar receivers and other components.

Keywords: Ceramics, High Temperature Design, Solar Receivers

1. Introduction

Efficiency goals continue to push solar receiver temperature outlet temperatures higher [1], meaning the receiver materials themselves must survive high temperature for long target plant lives. Past work suggests achieving a viable receiver design with metallic materials may be challenging [2] but ceramic materials, with their excellent high temperature properties, might be a viable solution [3]. However, the engineering design of high temperature ceramic components is very different from those of metallic materials, meaning there is a need to provide the CSP community with applicable methods and software tools.

We have developed an extension of the open-source receiver evaluation and life prediction tool, *srlife*, that can evaluate the expected reliability of ceramic receivers operating at high temperatures. The current version of the software assumes that failure will be time-independent, but future extensions of the analysis method will consider time-dependent failure.

The manufacturing process produces ceramics with an inherent, initial population of subscale flaws. Thermal and mechanical loads can cause these flaws to grow unstably, resulting in component failure, as ceramics are typically brittle materials. srlife analyzes the receiver stresses and temperatures under the user-provided thermomechanical loads and processes the resulting stress/temperature history using one of a variety of ceramic failure models, mostly developed through past work at NASA for aerospace components [4]. The result is an expected probability of failure for each tube in the receiver, which can be combined into the overall reliability of the receiver.

Evaluating this reliability requires several analysis steps, first to determine the component temperatures and stresses and then to process this information into the component reliability. The process requires several types of material data, including information on the thermal and mechanical response of the ceramic material, the thermal properties of the system working fluid, and the Weibull statistics describing the basic reliability and strength of the ceramic material.

This paper outlines the process of evaluating the expected reliability of a high temperature tubular panel ceramic solar receiver. In the process, the paper identifies the types of material data required to complete the analysis and how that data can be obtained either from the literature or a dedicated experimental test campaign. We illustrate the use of the new capability by comparing the performance of a reference solar receiver constructed from both Ni-based superalloys and engineering ceramics. Finally, the paper concludes by describing the additional work required to complete the ceramic analysis package in srlife, notably extending the capability to time-dependent failure, and describes a path towards the wider acceptance and use of ceramic components in the CSP community.

2. Evaluating the reliability of a ceramic receiver

Figure 1. Flow chart illustrating the analysis steps in calculating the overall receiver reliability.

The new ceramic life estimation capability builds on the existing metallic life estimation modules in srlife [5]. Figure 1 shows the general process of evaluating a ceramic tubular receiver. This section walks through some of the details of this process, focusing on differences in the ceramic and metallic analysis procedures.

2.1 Receiver geometry and loading

While srlife can be applied to analyze any type of CSP component, the code is structured to help the user quickly analyze tubular receivers. The software provides a data structure to define the geometry and loading conditions on a tubular panel receiver. The user provides the number of tubes in each panel, the tube geometry (thickness, outer diameter, and height), and the thermal and mechanical boundary conditions loading each tube in the receiver. These boundary conditions include the internal tube pressure as a function of time, the net incident flux on the outside diameter of each tube (likely calculated by another software package), and the details of convective heat transfer into the receiver working fluid (see next section). To reduce the cost of the analysis the user can analyze a limited subset of representative tubes in each panel. For example, the actual panel may have 100 tubes, but the user might elect to analyze only 2 or 3 tubes in the panel and let the analysis results for these tubes represent the response of the remaining tubes.

For a ceramic tubular receiver, this part of the software remains exactly the same as for the original, metallic analysis module. The only difference is that srlife now provides two ceramic options in the built-in material library: commercial SiC and properties for a Ti_3SiC_2 MAX phase material. The subsequent subsections discuss the types and sources of the data for these materials as they come up in the analysis.

2.2 Thermal analysis

srlife now includes a simple thermohydraulic analysis module to calculate heat balance in each flow path in the receiver. This is a change from the original version of the software, where the user had to provide the fluid temperature as a function of position along the flow path and time (likely calculated from an external thermohydraulic solver). The new thermohydraulic capability could be applied to calculate the temperatures in either a metallic or ceramic receiver. However, we identified the need to integrate a thermohydraulic solver into srlife to fairly compare equivalent metallic and ceramic receiver designs. A fair comparison here would consider equivalent receivers from the plant system perspective. The key characteristics of the receiver in the context of the plant system are the incident flux, the inlet temperature, the outlet temperature, and the flow rate. However, ceramic and metallic receivers have very different thermal properties. So, if we were to fix three of these four parameters for a metallic and ceramic design the fourth parameter would be different for the two materials.

Instead, we developed the thermohydraulic solver to allow users of srlife to quickly alter other aspects of the receiver design, for example the tube thickness, iterate through the thermohydraulic analysis, and alter the design to keep the system characteristics of the receiver fixed for multiple receiver materials. This iteration would be cumbersome if each time the user had to transfer data back and forth between srlife and an external thermohydraulic solver.

The integrated thermohydraulic solver is fairly basic. It neglects the effect of friction and assumes a constant flow velocity along each flow path in the receiver. It assumes perfect mixing in the panel manifolds, so that each tube in a panel has the same starting and ending temperature, and further assumes a linear temperature variation along each tube from inlet to outlet. As with all the analysis modules in srlife, the user can represent the panel response by explicitly modeling only a few tubes (say the hottest and coldest) and use these tube responses to represent the response of the entire panel.

The key balance equation is the relation between the heat transferred out of each tube via mass flow and into each tube through convection from the tube into the working fluid:

$$\dot{Q}_{i,flow} = \dot{Q}_{i,conv} \tag{1}$$

where the subscript indicates each panel in each flow path in the receiver. The heat transfer out of the tube by mass transfer is easy to construct given the fluid temperature, heat capacity, and mass flow rate. The convective heat transfer into the fluid however depends also on the details of heat transfer in the solid tube. To solve this heat transfer problem we use the existing transient heat transfer solver module already built into srlife. This is a 1D, 2D, or 3D finite difference, transient heat transfer code custom built for srlife. We couple this solver into the thermohydraulic solver with Picard iteration. The individual metal (finite difference) and fluid (simple heat balance) solvers use a full Newton-Raphson solution method with quadratic convergence. The Picard iteration between the two codes means the overall convergence of the composite solver is less than quadratic. We could improve this in the future with a full Newton coupling, if it proves to be the performance bottleneck in the overall software package.

The required material properties for the thermohydraulic solver are the thermal conductivity and diffusivity of the solid ceramic, obtained from the literature for SiC and MAX phase materials, and the heat capacity, density, and convective heat transfer correlation for the receiver working fluid. *srlife* provides thermal-fluid data for 32% $MgCl_2$/68% KCl salt and supercritical CO_2, using literature data.

2.3 Mechanical analysis

Given the internal pressure in each tube and complete tube temperature distribution, srlife then uses the existing structural analysis module from the original metallic life estimation module to calculate the tube stress and strain fields. This calculation applies a 1D, 2D, or 3D finite element of each tube, with the tube mechanical boundary conditions setup to approximate the effect of tube restraint caused by the panel manifold and/or interpanel structural connections.

The structural solver does not feed back into the thermal analysis – the tube deflections are not large enough to significantly affect thermohydraulic heat transfer through the fluid or transient heat transfer in the tube themselves. The coupling here is therefore "one way" – the temperatures from the heat transfer analysis are imposed on the structural model.

The ceramic evaluation module reuses this code unchanged. Currently, the module applies a linear elastic model for the mechanical response of the ceramic. The required material data is the material Young's modulus, Poisson's ratio, and coefficient of thermal expansion. srlife includes these properties for commercial SiC and MAX phase ceramics, using data from the open literature.

2.4 Reliability calculation

At this point the software has calculated the stress and temperature field for each tube in the receiver. The final step in the analysis is to convert this to the reliability of the receiver as a whole, defined as the probability that some part of the receiver will fail by fast fracture under the calculated stresses and temperatures. We use the methods developed by NASA for the CARES/LIFE [4] software to calculate the receiver reliability. A companion paper [6] defines these methods in greater detail, discusses how we verified our implementation, and provides recommendations on which of the several ceramic failure models we suggest for use in receiver analysis.

Ceramic failure is size dependent – larger volumes of material are more likely to contain a critical flaw when compared to smaller volumes of material. srlife uses the element volume from the structural analysis as the basic integration volume to calculate the reliability. The software then combines the element reliabilities to calculate the overall reliability of the system:

$$P_{fv} = 1 - \exp\left\{-\frac{2k_{Bv}}{\pi}\sum_{i=1}^{n_{elem}} V_i \int \sigma_{e,i}^{m_v} dA\right\} \tag{2}$$

where P_{fv} is the reliability, n_{elem} is the number of finite elements, in the model, and V_i is the element volume. The inner integral is over the unit sphere describing all potential failure planes. $\sigma_{e,i}^{m_v}$ is an effective stress value calculated for each element. The effective stress encodes assumptions on the failure model and the assumed flaw shape. The companion paper describes the various options in greater detail [6]. Finally, k_{Bv} is the Batdorf coefficient and m_v the Weibull modulus. Both of these are related to a Weibull model for the uniaxial failure of the material, which in term can be determined from bend test data. These are therefore material data specific to the ceramic type and specific heat of material under consideration. *srlife* provides reference data for SiC and MAX phase materials, now relying on a combination of literature data and test data collected at Argonne National Laboratory.

3. Example problem

The addition of thermohydraulic and reliability analyses into srlife allows making a fair comparison between metallic and ceramic receivers. As an example, demonstration, here we compare the performance of a reference receiver model between Ni-based superalloys, such as A740H and A282, and an engineering ceramic, SiC. The model is a 21 m tall, 17 m diameter, 360° external cylindrical receiver with a thermal design power of 500 MW_t and maximum direct normal irradiance (DNI) of 750 kW/m^2. The heat transfer fluid (HTF) is 32% $MgCl_2$/68% KCl salt with a constant inlet temperature of 550 °C and nearly constant outlet temperature of 720 °C. The recevier consists of two serpentine flow paths, each containing six panels and one hundred tubes per panel. Figure 2 shows the heat flux map on the receiver at noon and the variation in flux and HTF mass flow rate during the day. Figure 2 also plots the HTF and tube crown temperatures determined from thermohydraulic analysis. The figure plots these temperature along a flow path for the hottest and coldest tubes in the panels. Note we simulated only the hottest and coldest tubes in each panel because this provides a conservative estimation of stresses in the tubes [5, 7]. Figure 3a shows the temperature distribution in the hottest tubes at noon for recevier with 2 mm thick SiC tubes.

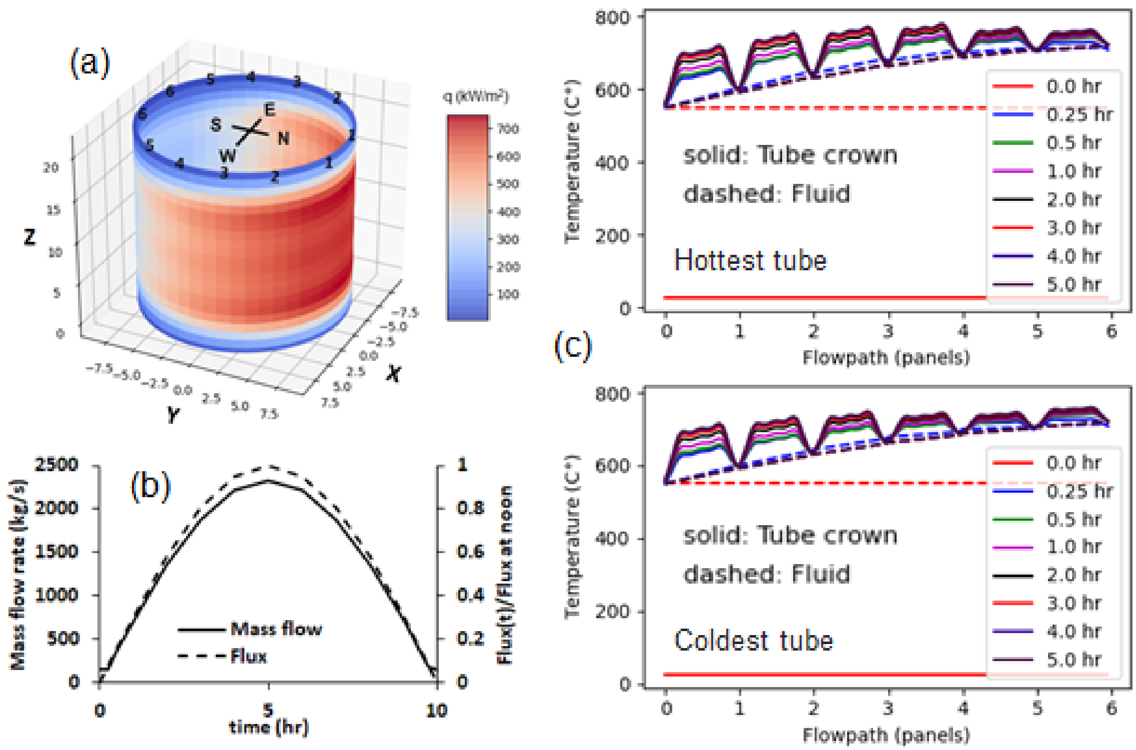

Figure 2. (a) Heat flux map on the recevier at noon, (b) variation in heat flux and HTF mass flow rate during the day, (c) Changes in HTF and tube crown temperatures (shown for the hottest and coldest tubes in panel) along the flow path from the start of the day to noon. Tube material: SiC, tube thickness: 2 mm.

Using the temperature results from thermohydraulic analysis and given the pressure of the HTF, srlife performs structural analysis. Table 1 lists the required material parameters for different tube materials to perform the structural analysis. We employed different material models for the structural analysis of the SiC tubes and the metallic tubes. An elastic material model was used for the SiC tubes, while an elastic-creep model was utilized for the metallic tubes. The elastic-creep model incorporates additional parameters to calculate creep strain, ε_c, employing the Kock-Mecking model.

$$\varepsilon_c = \dot{\varepsilon}_0 e^{B\mu b^3/(AkT)} \left(\frac{\sigma}{\mu}\right)^{-\mu b^3/(AkT)} t \tag{3}$$

where μ is the material shear stress given as $\mu = \frac{E}{2(1+\nu)}$, k is the Boltzmann constant (= 1.38 x10^{-23} J/K), T is the absolute temperature, b is a characteristic Burgers vector, $\dot{\varepsilon}_0$ is a reference strain rate, and A and B are constants. Table 2 lists the additional parameters required for the Kock-Mecking model applied to the two metallic alloys.

Table 1. Elastic modulus, Poisson's ratio, and instantaneous co-efficient of thermal expansion of SiC, A740H, and A282.

Temp. (°C)	Elastic modulus (GPa)			Poisson's ratio (v)			Instantaneous CTE (μm/mm/°C)		
	SiC	A740H	A282	SiC	A740H	A282	SiC	A740H	A282
20	415	221	217	0.16	0.31	0.32	4.62	12.4	12.1
300	408	187	202	0.16	0.31	0.31	5.14	14.3	13.5
600	401	186	183	0.16	0.31	0.35	5.54	16.0	14.7
800	397	169	166	0.16	0.31	0.36	5.72	20.4	19.6
900	394	160	154	0.16	0.31	0.36	5.83	16.5	23.7

Table 2. Kock-Mecking model parameters for A740H and A282.

Parameters	A740H	*A282*
$\dot{\varepsilon}_0$ (hr^{-1})	1.0×10^{13}	5.0×10^{8}
B (mm)	2.53×10^{-7}	2.53×10^{-7}
A	-9.6295	-12.1119
B	-0.1470	0.0115

We considered HTF pressures of 2.2 MPa, 2.6 MPa, and 3.2 MPa, respectively, for 1 mm, 2 mm, and 3 mm thick tubes. The panels are mechanically decoupled but the tubes in a panel are rigidly connected to the tube manifold. Figure 3b shows the axial stress distribution of normal stress components at noon in the hottest tubes when the receiver is constructed using 2 mm thick SiC tubes. As the figure indicates, the axial stress component is significantly higher than the other stress components. This is expected as the tubes are subjected to axial bending due to circumferentially large temperature difference as well as axial constraint imposed by the tube manifold. However, the high axial stresses are mostly compressive which is favorable for ceramics as ceramics are much stronger in compression than tension.

In the final step, srlife performs the reliability analysis of individual ceramic tubes considered in analysis using the temperature and stress fields determined above. Table 3 lists the Weibull modulus and scale parameter for SiC. These parameters are required to calculate reliability of SiC tubes. Table 4 lists the minimum tube reliability of the reference receiver for different tube thicknesses. The reliability decreases with tube thickness. The opposite trend may occur for receivers operating with a high pressure HTF fluid such as sCO_2.

Table 3. Weibull modulus and scale parameter for SiC.

Temperature (°C)	Weibull modulus, m	Scale parameter, σ_0 (MPa-(mm)^(3/m))
25	10.70	507
800	10.70	467

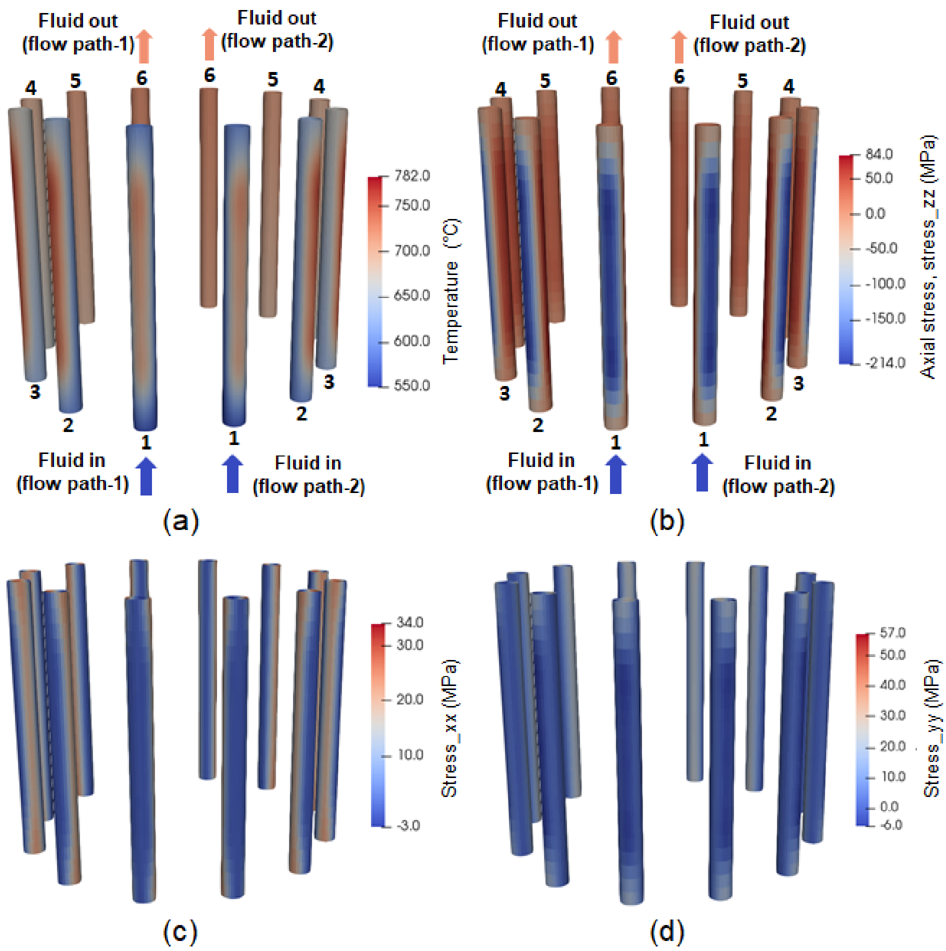

Figure 3. Temperature and normal stress distributions in the hottest tube of each panel at noon. Tube material: SiC, tube thickness: 2 mm.

A fair comparison between the metallic and ceramic receivers should consider the manufacturability of the receiver tubes. Manufacturing 1 mm thick ceramic tubes may not be possible. Table 4, therefore, lists the reliability of SiC receivers for tubes with thickness (1 mm), the same as the metallic tubes, and for thicker SiC tubes (2 mm and 3 mm) that can be manufactured with current techniques. For all three thicknesses, the time-independent reliability of SiC receiver is excellent in contrast to the very short life of the metallic receiver – especially since the estimated life of metallic receivers is based on average material properties and, therefore, might be a reasonable representation of a median life estimate corresponding to a reliability of 0.5.

Table 4. Comparison between metallic and ceramic receivers. Reliability of ceramic receiver is based on the minimum tube reliability and calculated using Griffith's tensile stress criteria for a penny-shaped crack (see [6] for details). Life of metallic receiver is based on the shortest tube life due to creep-fatigue damage accumulation.

Material	SiC			A740H	A282
Tube thickness (mm)	1	2	3	1	1
Reliability	0.994	0.987	0.976	-	-
Life (days)	-	-	-	44	96

4. Conclusions

4.1 Summary

This paper describes the implementation of a time-independent ceramic analysis module in the open source srlife software package. This new capability allows users to evaluate the reliability of high temperature ceramic solar receivers and other CSP components. We demonstrated the new capability by evaluating a SiC ceramic tubular panel receiver and comparing the results to equivalent metallic receiver designs. The software, including the underlying material data, is available for use by the community under an open-source license (see data availability below).

4.2 Future work and community decisions

The current ceramic assessment capability in srlife assumes time-independent failure. That is, the subscale flaw distribution of the ceramic material remains fixed to the initial, as-manufactured flaw distribution and only the thermomechanical loading varies as a function of time. In actuality, high temperature fatigue and creep crack growth will alter the subscale flaw distribution as a function of time as these mechanisms grow the initial subscale flaws via subcritical crack growth. A complete description of the reliability of high temperature ceramic CSP components would include modelling this subcritical crack growth. Essentially, this alters the strength of the material, as described by its Weibull statistics, as a function of time, temperature, mechanical load, etc. Combining subcritical crack growth models of this kind with the existing time-independent evaluation capability in srlife would provide the required modelling capability. However, additional time-dependent ceramic test data will be needed to parameterize the models.

This work also leaves open a key question – what is the required reliability of a given CSP component? The methodology developed here provides the reliability of the component – the probability that the component will *not* fail by fast fracture under the provided thermo-mechanical load history. The final, time-dependent failure models will provide the same reliability probability but now as a function of time – the probability that the component will not fail for a given component design life. Translating this reliability into a design metric will require the CSP community to ascertain an acceptable reliability. For the moment we bypass this requirement by comparing the ceramic designs to the best-estimate service lives of metal components. As the metallic life calculation uses best-estimate, average material properties the corresponding ceramic reliability would logically be 50%. However, this is clearly not acceptable for a design analysis, where some safety margin is required.

Determining the required reliability will need input from CSP system developers, utilities and other customers, and the broader design community. Different reliability targets could be used for different types of components, to reflect relative risks associated with component failure. Alternatively, the community could adopt a system reliability approach that tailors the required reliability of a component to its role the plant system. In addition to this critical design decision, more work on the fabrication and joining of ceramic components will be required before they can be put into service. However, the results reported here strongly support continued work on integrating ceramic components into CSP systems and engaging with CSP developers to disseminate the knowledge and experience they would need to put ceramic components into service.

Data availability statement

The material data used in the sample problem is contained in the distribution of the *srlife* software, available at https://github.com/Argonne-National-Laboratory/srlife.

Underlying and related material

The source code for *srlife* and the input data for various examples are available at https://github.com/Argonne-National-Laboratory/srlife.

Author contributions

M. C. M. modified the *srlife* software and contributed to the initial and final drafts of the manuscript. P. C. added the ceramic failure models to *srlife*. B. B. ran the example analysis and helped write the draft and final manuscripts. D. S. helped administer the project and collect ceramic failure data. All reviewed and edited the final manuscript.

Competing interests

The authors declare no competing interests.

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