Proceedings of the 9th International Conference on Energy Sustainability
ES2015
June 28 – July 2, 2015, San Diego, California, USA

SAND2015-2275C

PowerEnergy2015-49489

DESIGN REQUIREMENTS FOR DIRECT SUPERCRITICAL CARBON DIOXIDE RECEIVER DEVELOPMENT AND TESTING

Jesus D. Ortega
Sandia National Laboratories, Concentrating Solar Technologies Department
Albuquerque, NM 87185-1127, USA.

Sagar D. Khivsara
Indian Institute of Science, Dept. of Mechanical Engineering
Bangalore, KA 560012, India.

Joshua M. Christian
Sandia National Laboratories, Concentrating Solar Technologies Department
Albuquerque, NM 87185-1127, USA.

Clifford K. Ho
Sandia National Laboratories, Concentrating Solar Technologies Department
Albuquerque, NM 87185-1127, USA.

ABSTRACT
This paper establishes the design requirements for the development and testing of direct supercritical carbon dioxide (sCO2) solar receivers. Current design considerations are based on the ASME Boiler and Pressure Vessel Code (BPVC). Section I (BPVC) considers typical boilers/superheaters (i.e. fired pressure vessels) which work under a constant low heat flux. Section VIII (BPVC) considers pressure vessels with operating pressures above 15 psig [2 bar] (i.e. unfired pressure vessels). Section III, Division I – Subsection NH (BPVC) considers a more detailed stress calculation, compared to Section I and Section VIII, and requires a creep-fatigue analysis. The main drawback from using the BPVC exclusively is the large safety requirements developed for nuclear power applications. As a result, a new set of requirements is needed to perform detailed thermal-structural analyses of solar thermal receivers subjected to a spatially-varying, high-intensity heat flux. The last design requirements document of this kind was an interim Sandia report developed in 1979 (SAND79-8183), but it only addresses some of the technical challenges in early-stage steam and molten-salt solar receivers but not the use of sCO2 receivers. This paper presents a combination of the ASME BPVC and ASME B31.1 Code modified appropriately to achieve the reliability requirements in sCO_2 solar power systems. There are five main categories in this requirements document: Operation and Safety, Materials and Manufacturing, Instrumentation, Maintenance and Environmental, and General requirements. This paper also includes the modeling guidelines and input parameters required in computational fluid dynamics and structural analyses utilizing ANSYS Fluent, ANSYS Mechanical, and nCode Design Life. The main purpose of this document is to serve as a reference and guideline for design and testing requirements, as well as to address the technical challenges and provide initial parameters for the computational models that will be employed for the development of sCO_2 receivers.

INTRODUCTION
The *ASME Boiler & Pressure Vessel Code (BPVC)* provides the rules for the design, fabrication, and maintenance of fired and unfired pressure vessels [1]. It also provides a wide range of methods for high temperature and high pressure applications, the design criteria focuses mainly on traditional (e.g. coal-fired) boilers and superheaters, which are related, but not similar to CSP receivers. The *ASME Pressure Piping B31.1 Code* provides the guidelines for design and selection of pressurized tubes and pipes [2]. Typically, these codes are used for the design of conventional power boilers and superheaters.

Unfortunately, there are three main drawbacks of using the codes exclusively and without any modifications inclined to CSP applications:

1. Although *Section I* considers the design of power boilers and superheaters, it is mainly design for power plants which typically are convectively heated by flue gas at relatively low rates of thermal flux.
2. The large safety requirements developed for nuclear components in *Section III, Division I – Subsection NH* will require further simplifications since the level of conservatism in the creep-fatigue analyses is not necessary for CSP applications [3].
3. Using B31.1 design equation for pressurized pipes is only restricted to isothermal temperature of the tube,

therefore only pressure induced stresses are considered.

These limitations led to a set of simplified design rules based on the nuclear code were developed for CSP receivers were documented in an interim design standard for solar energy applications (SAND79-8183). This approach simplifies the design methodology for a creep-fatigue analysis with a cumulative damage approach [3]. Nonetheless, there has not been an updated release of a design requirements report that incorporates current computational design tools.

The aim of this work is to update the design elements previously used for solar power applications and establish the new design goals targeted by the SunShot Initiative while incorporating the use of computational design tools. A design requirements report has been compiled and will be on the process of becoming an interim report.

Solar Receiver Types

The solar receiver is a critical component in concentrating solar power plants [4]. Although, the receiver accounts for about 15% of the total plant investment cost [5], the receiver will dictate the efficiency and long-term performance of the solar plant. As the receiver absorbs the highly concentrated solar energy and transmits it to the heat transfer fluid, the durability of the tubes is of high importance for a viable design. Solar thermal receivers are generally classified into two main types:

Direct receivers, where the heat transfer fluid is used as heat transport medium and as the working fluid for the power block. The advantage of this type of systems is that it does not require a secondary heat exchanger to run the turbine. The receiver used in Solar One (figure 1a) uses water/steam as a heat transfer fluid which is directly used to feed the turbine. The main drawback of this type of receivers is the high operating pressures. Receiver examples include:

- Volumetric gas receiver
- Small particle-gas receiver (fluidized bed)
- Tubular gas receiver

Figure 1: a) Solar One Receiver (1981-1987) was a Water/Steam Receiver with thermal rating of 41 MW (175-516°C at 10 MPa) and b) Solar Two Receiver (1996-1999) was a Nitrate Molten Salt Receiver with thermal rating of 42.2 MW (288-566°C at ~2 MPa).

Indirect receiver are those where the heat transfer fluid/medium transports the heat to the working fluid for the power block. This method requires an appropriate heat exchanger to be designed. The receiver used in Solar Two (figure 1b) uses molten salt as a heat transfer fluid which heats the steam that is fed to the turbine. Receiver examples include:

- Volumetric gas receiver
- Tubular gas receiver
- Tubular liquid receiver
- Falling-film receiver
- Solid particle receiver

Using sCO_2 as Working Fluid

Carbon dioxide (CO_2) has been proposed as a heat transfer and/or working fluid because of the moderate value of its critical pressure, its chemical stability and relative inertness, sufficient knowledge of its thermodynamic properties, non-toxicity, abundance and low cost [6].

In the case of carbon dioxide (CO_2), the critical point is 7.38 MPa and 30.98°C [6]. Supercritical CO_2 recompression cycles are able to achieve the same efficiency as helium Brayton cycles, which operate at much higher temperatures, as observed in figure 2.

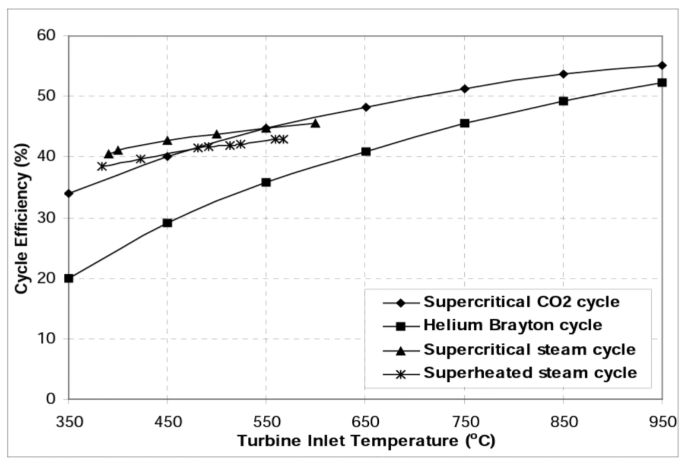

Figure 2: Cycle efficiency comparison of advanced power cycles [5].

The supercritical CO_2 cycle at turbine inlet temperature of 550°C achieves 46% thermal efficiency, which is the same as the helium Brayton cycle at 800°C (if all losses are taken into account). From the structural design standpoint, lower fluid temperatures denote lower surface temperature, which means lower thermal stresses across the tube thickness. Tubular receivers that employ sCO_2 as the heat transfer fluid are a likely possibility as the small diameter tubes may enable the high pressures required for the supercritical phase.

DESIGN GOALS

Part of the SunShot initiative aims for advanced receiver designs to accommodate higher temperature power cycles that can achieve greater than 50% net thermal-to-electric conversion efficiency [7]. The technical targets for these advanced receivers are:

- Exit temperatures ≥ 650 °C
- Average annual thermal efficiency ≥ 90%
- Number of diurnal cycles to failure ≥ 10,000
- Cost of receiver < \$150/ kW_{th}

These targets are the guidelines used for the development of the design requirements.

MODELING INPUTS

Computational design software constitutes a very important part of the design process. ANSYS Workbench enables the user the ability of coupling different types of analysis. ANSYS Fluent is a computational fluid dynamics (CFD) software that contains physical modeling capabilities such as fluid flow, turbulence, heat transfer and reactions and many more models for multiple applications. ANSYS Structural is a finite element analysis (FEA) software that focuses mainly on providing reliable linear and non-linear structural analyses. nCode DesignLife provides fatigue-life and creep-damage predictions using FEA. nCode can be coupled to ANSYS Structural to provide the initial loading conditions for the models. These three tools are currently used for many application and they should be incorporated in the design and evaluation of the new generation of solar thermal receivers.

Thermal-Structural Analysis

The procedure that can be followed is presented by Neises et al. [8], which focuses on the development of an analytical model using the pressurized cylinder equations. Each component is composed of the mechanical and thermal stresses which are resulting stresses from the pressure and thermal load respectively. The results obtained from the analytical models will be used to build a finite element analysis (FEA) structural model using ANSYS Structural.

A static thermal-structural analysis is a type of finite element analysis (FEA) that couples the thermal solution or temperature distribution and numerically approximates the resulting stress distributions throughout a designed part. These stress levels are used to estimate the creep-fatigue accumulated damage using the same methodology used by Neises et al [8]. For receivers being developed as a part of SERIIUS, the teams are using ANSYS Fluent and ANSYS Structural for the thermal-structural coupling along with nCode Design Life to estimate the creep and fatigue accumulated damage which will yield the time to failure of the receiver.

The analyses require the user to know several properties of the materials to be used. Table 1 shows the basic properties required in the individual analyses.

Figure 3 shows an example of a thermal-structural analysis performed by Ortega et al. [9] in which a direct tubular receiver is analyzed. They use a coupled temperature distribution to numerically compute the stresses and strains throughout a tube. These values are then used to estimate the lifetime of the receiver under a simplified performance condition.

Thermal-Fluid Analyses	Structural Analyses	Creep-Fatigue Analyses
Fluid	**Solid**	**Solid**
Heat Capacity	Coefficient of Thermal Expansion	Stress-Life or Strain Life Parameters
Density	Young's Modulus	
Thermal Conductivity	Poisson's Ratio	Larson-Miller Master Curve
Viscosity	Yield Strength	
Solid	Ultimate Strength	
Heat Capacity	Density	
Density		
Thermal Conductivity		

Table 1: For the different analyses to be performed these properties are required. The temperature dependence of these properties should be modeled in order to obtain accurate results.

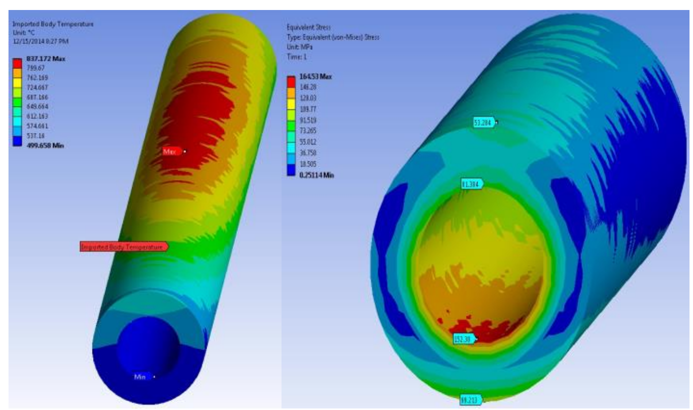

Figure 3: a) Temperature distribution along the tube for ~700 kW/m^2 and b) Equivalent stress distribution with a cross-sectional cut along the region with highest temperature [8].

It is important to perform a mesh independence analysis in order to assure that the mesh being used is appropriate for the analysis.

Thermal-Fluid Analysis

For receivers being developed as a part of SERIIUS, the teams are using ANSYS Fluent for the thermal-fluid analysis. This will facilitate the coupling for the thermal-structural analysis. Figure 4 shows an example of a thermal-fluid analysis performed by Ortega et al. [10] in which a simplified direct tubular receiver is analyzed. They use a coupled optical-thermal-fluid analysis that estimates the temperature distribution along the tubes of the receiver and the thermal efficiency of different arrangements of tubes on a receiver.

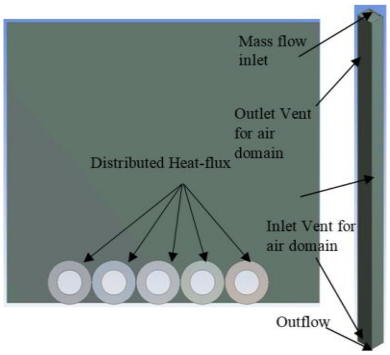

Figure 4a: Domains and boundary conditions used in the CFD model [9].

The CFD model consists of three domains. An internal domain will consider the heat transfer from the inner wall of the tube to the sCO_2. The second domain considers the thermal conductivity axially, radially and tangentially along the tube. And the third domain is an air domain surrounding the receiver; this domain will capture the radiative and natural convective losses.

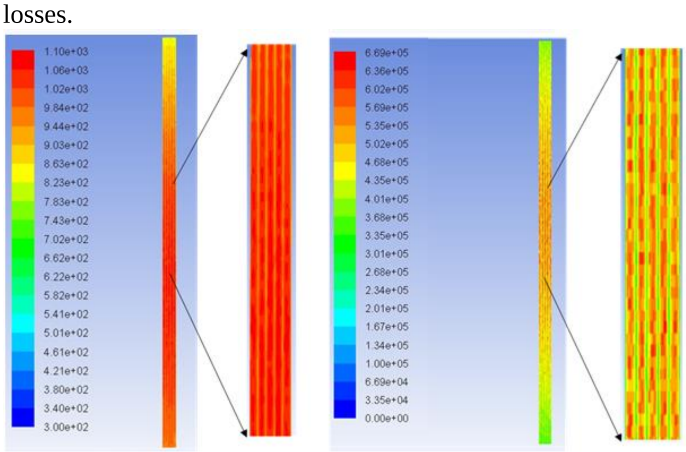

Figure 4b: Temperature and heat flux contours of the case corresponding to 0 degree offset and ~700 kW/m^2 [9].

As mentioned before, it is important to perform a mesh independence analysis in order to assure that the mesh being used is appropriate for the analysis. Also, mesh independence must be performed on the solid part to determine the number of elements required across the thickness of the receiver.

DESIGN REQUIREMENTS

The design requirements have been divided into five main categories. This paper provides some general requirements listed on the design requirements report.

General Requirements

- The receiver must not place any person undertaking authorized work in accordance with 'Workplace Health and Safety guidelines' (must be documented) and defined 'Construction, operation and maintenance procedures' (must be documented) in danger of injury or suffering illness during:
    - Normal operation
    - Maintenance activities
    - In the case of system failure
- All tube and header welds require non-destructive evaluation to verify weld quality and integrity. Each panel will be hydro-tested to 1.5 times the operating pressures in accordance with ASME code requirements. In addition, each panel should be pressurized with helium and the panel assembly helium leak test should be conducted in accordance with *ASME BPVC Section V*.
- The receiver support structure holding the inlet and outlet header should allow free expansion of the tubes if the design requires it to have thermal growth.
- Appropriate thermal insulation panels must be attached to the rear side of each receiver tube to accommodate the panel thermal expansion and contraction cycles. The design should also consider the presence of moisture if such a situation is anticipated.
- The receiver mounting frame interfaces with the receiver assembly support frame and should be designed to accommodate dead loads, thermal loads and wind loads.
- Individual panel tubes must be designed to be replaced during an eight-hour night-time maintenance shift. The cutting and welding operations should be performed from inside the receiver. Tube removal and new tube fit-up occur from the outside. The receiver design and placement must encompass field welding equipment, work access stands, lighting, and environmental shielding. Environmental shielding must permit the welding operations to be conducted with wind speeds up to 22 m/s (50 mph).

Operational and Safety Requirements

- The startup and shutdown time should not be more than 30 minutes.
- During daily plant start-up and after long periods of cloud cover; control of the receiver mass flow rate must be combined with the heliostat aiming strategy in order to prevent overheating of the receiver tubes.
- The receiver should be able to withstand the heat flux variations throughout the diurnal cycle.
- The reference DNI for design of the receiver should be based on the average DNI on a clear, summer day at the deployment location.
- Short term fluctuations due to cloud cover should preferably be taken care of by the thermal mass inside the receiver. Acceptable mass flow rate fluctuation should be estimated.

- In the absence of the working fluid due to unprecedented reasons, there should be a feedback to the concentrator to prevent the burnout of the receiver.
- In the event of pump malfunction or power loss, the receiver inlet should be able to supply the fluid to the receiver for at least the time till the concentrators are deflected away from the receiver.
- During operation, heated parts of the receiver should not be accessible.
- Contact of the compressor oil and other lubricants with the high temperature parts in the sCO_2 receiver should be prevented, as it can lead to an explosion.
- To ensure that the receiver does not burnout during operation, infrared cameras should be permanently located in the concentrator field and directed at the receiver surface to monitor its temperature.
- Thermocouples that are tack-welded to the back of tubes should have flexible leads with enough slack so that tube movement caused by thermal growth would not break the thermocouple–to tube-welds joints.
- Outline and make provisions to clearly alert the operator when out-of-specification conditions occur in any part of the receiver.
- Water intrusion during rain can cause damage to the control systems and the receiver components such as insulation. Receiver design should account for such an intrusion.
- Provide a roof which can protect the receiver from windy rains and ensure proper arrangements to carry the collected rainwater away from the receiver and its auxiliary equipment.
- Receiver should be equipped with pressure relief valves at appropriate locations depending on the design of the receiver.

Materials and Manufacturing Requirements

- The long term operation and reliability of solar central receivers generally favors the collection of energy at constant temperature. The cloud transients encountered during daily plant operations can cause the receiver temperatures to fluctuate with time thereby inducing cyclic thermal stresses. These stresses can substantially reduce the receiver lifetime.
- The materials used by the receiver, insulation, instrumentation and heat transfer fluid should not be toxic, flammable, carcinogenic or explosive
- The metals considered in the design of the receiver should be resistant to corrosion due to the exposure to air and sCO_2.
- The receiver material should not react with sCO_2 at the specified operating conditions and for the specified continuous operation time.
- The elevated temperatures in the receiver alter the oxidation rate of the coating. This consideration is important for specifying the coating material and its thickness.
- The metal used for the tubes must be able to withstand the internal pressure at elevated temperatures for the intended time of operation and also sustain safely under cyclic loading. Some popular materials under consideration are: Haynes 230, Inconel 617, Inconel 625, Hastelloy and Incoloy 800.
- The absorber coating should be able to withstand the high heat flux due to the concentration and the temperatures should not rise to unacceptable values. Pyromark series paints are under consideration for most ventures of sCO2 receivers.
- The receiver design should have the tube placement such that it allows necessary accessibility for welding during assembly and maintenance of the receiver.

Instrumentation Requirements

- The sampling rate of the instrument should be optimized based on the transients in the receiver.
- Wherever possible, non-intrusive measurement techniques (such as IR thermal imaging instead of using thermocouples) should be preferred.
- Data collection method should not interrupt the operation of the receiver and result in the modification of the working of the receiver.
- Appropriate corrections should be applied to the acquired data.
- Receiver control strategy should aim to maintain the outlet temperature of the working fluid by controlling the mass flow rate throughout the receiver. This can accomplished by sensing the temperatures and heat fluxes on the receiver and feeding back the signals to a controller which alters control valve opening and/or pump speed to the required mass flow rate.
- A feedback loop should provide information to the concentrators with accurate temperature readings to avoid receiver overheating.

Maintenance and Environmental Requirements

- Cleaning of the relevant receiver parts should be convenient and efficient.
- The layout of the piping and arrangement of receiver panels should be such that there is no congestion for the maintenance personnel to inspect the tubes, insulation and to recoat the tubes with the absorbing paint.
- Leaked sCO_2 should have a guided path so as to recapture it or allow it to escape safely to environment.

CONCLUSIONS

- A set of requirements has been compiled for performing detailed thermal-structural analyses of solar thermal receivers subjected to a spatially-varying high-intensity heat fluxes. Using the *ASME BPVC* and *ASME B31.1 Code* along with appropriate modifications, it is possible to achieve the reliability requirements in sCO_2 solar power systems. The last design requirements document of this kind was an interim Sandia report developed in 1979 (SAND79-8183), but it did not address the use for sCO_2 receivers.

- Modeling strategies, guidelines and input parameters required in computational fluid dynamics and structural analyses of sCO_2 receivers utilizing ANSYS Fluent, ANSYS Mechanical, and nCode Design Life have been discussed.
  - Various subsets of requirements for design, development and testing a sCO_2 receiver have been presented in this work.
  - More detailed examples and guidelines will be available soon in the interim Sandia design requirements report.

ACKNOWLEDGMENTS

This research is based upon work supported by the Solar Energy Research Institute for India and the U.S. (SERIIUS) funded jointly by the U.S. Department of Energy subcontract DE AC36-08G028308 (Office of Science, Office of Basic Energy Sciences, and Energy Efficiency and Renewable Energy, Solar Energy Technology Program, with support from the Office of International Affairs) and the Government of India subcontract IUSSTF/JCERDC-SERIIUS/2012 dated 22nd Nov. 2012

REFERENCES

1. *ASME Boiler and Pressure Vessel Code*. New York, NY: American Society of Mechanical Engineers, 2013.

2. *ASME Power Piping Code*. New York, NY: American Society of Mechanical Engineers, 2014.

3. I. Berman, A. C. Gangadharan, G. D. Gupta, and T. V. Narayanan, *An Interim Structural Design Standard for Solar Energy Applications*, Sandia National Laboratories, Livermore, CA, Report No. SAND79-8183, 1979.

4. Ho, C.K. and B.D. Iverson, 2014, *Review of high-temperature central receiver designs for concentrating solar power*, Renewable & Sustainable Energy Reviews, 29, p. 835-846

5. Pitz-Paal R, Dersch J, Milow B., European concentrated solar thermal roadmapping (ECOSTAR): roadmap document. ECOSTAR,SES6-CT-2003-502578, http://www.promes.cnrs.fr/uploads/pdfs/ecostar/ECOSTAR. Summary.pdf; 2005.

6. Dostal V., "A supercritical carbon dioxide cycle for next generation nuclear reactors," PhD Thesis, Nuclear Engineering, (2004) Massachusetts Institute of Technology.

7. *SunShot Concentrating Solar Power (CSP) R&D*, Financial Assistance Funding Opportunity Announcement, from http://energy.gov/eere/sunshot/receiver-rd-csp-systems

8. T. W. Neises, M. J. Wagner, A. K. Gray, *Structural Design Considerations for Tubular Power Tower Receivers operating at 650 C*, Proceedings of the 8th International Conference on Energy Sustainability (ES2014), Boston, MA, June 30th – July 2nd 2014, ASME Paper No. 6603.

9. J. D. Ortega, J. M. Christian, C. K. Ho, *Structural Analysis of a Directly Heated Tubular Solar Receiver for Supercritical CO2 Brayton Cycle*, Proceedings of the 9th International Conference on Energy Sustainability (ES2015), San Diego,CA, June 28th – July 2nd 2015, *To be published*.

10. J. D. Ortega, S. D. Khivsara, J. M. Christian, J. E. Yellowhair, C. K. Ho, *Coupled Optical-Thermal-Fluid Modeling of a Directly Heated Tubular Solar Receiver for Supercritical CO2 Brayton Cycle*, Proceedings of the 9th International Conference on Energy Sustainability (ES2015), San Diego,CA, June 28th – July 2nd 2015, *To be published*.