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SERIIUS-MAGEEP Visiting Scholars Program

Final Report

Sagar D. Khivsara

Ph.D. Student

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Indian Institute of Science, Bangalore, India

Project Name: Coupled optical/thermal/fluid analysis and design requirements for operation and testing of a supercritical CO_2 solar receiver

Project Supervisor(s): Dr. Cliff Ho (Sandia National Laboratories, Albuquerque, US)

SERIIUS Project #: CSP-1 High-temperature, pressurized CO_2 receiver

1. Introduction and Description of Research Objectives

Recent studies have evaluated closed-loop supercritical carbon dioxide (s-CO_2) Brayton cycles to be a higher energy-density system in comparison to conventional superheated steam Rankine systems. At turbine inlet conditions of 923K and 25 MPa, high thermal efficiency (~50%) can be achieved. Achieving these high efficiencies will make concentrating solar power (CSP) technologies a competitive alternative to current power generation methods. To incorporate a s-CO_2 Brayton power cycle in a solar power tower system, the development of a solar receiver capable of providing an outlet temperature of 923 K (at 25 MPa) is necessary. To satisfy the temperature requirements of a s-CO_2 Brayton cycle with recuperation and recompression, it is required to heat s-CO_2 by a temperature of ~200 K as it passes through the solar receiver. Our objective was to develop an optical-thermal-fluid model to design and evaluate a tubular receiver that will receive a heat input ~1 MWth from a heliostat field.

We also undertook the documentation of design requirements for the development, testing and safe operation of a direct s-CO_2 solar receiver. 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 s-CO_2 receivers.

2. Methodology

The ray-tracing tool SolTrace was used to obtain the heat-flux distribution on the surfaces of the receiver. Computational fluid dynamics (CFD) modeling using the Discrete Ordinates (DO) radiation model was used to predict the temperature distribution and the resulting thermal efficiency of the receiver. The effect of flow parameters and receiver geometry (Fig.1) were studied. The receiver surface temperatures were found to be within the safe operational limit while exhibiting a receiver thermal efficiency of ~85%.

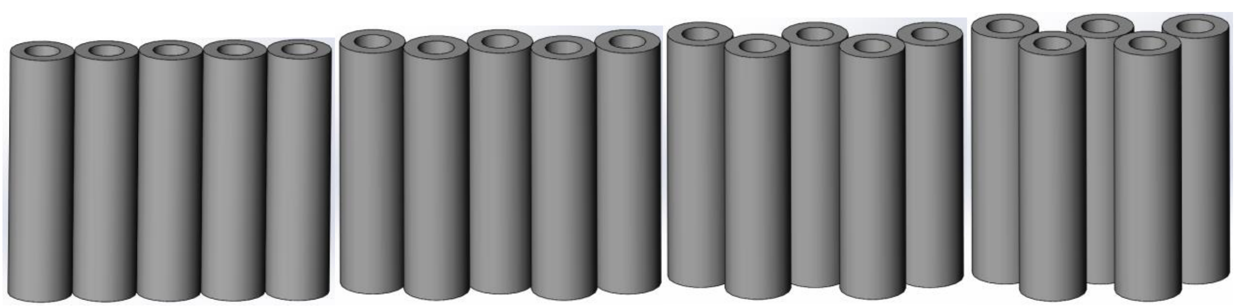

Figure 1. Tubes with offsets of 0°, 15°, 30°, 45° (L to R) [Provisional patent submitted]

There are five main categories in the design requirements document: Operation and Safety, Materials and Manufacturing, Instrumentation, Maintenance and Environmental, and General requirements. It 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 aim of this work is to update the design elements previously used for solar power applications and outline the new design goals targeted by the SunShot Initiative while incorporating the use of computational design tools. A draft of the design requirements report has been compiled and it will soon become an interim report at Sandia National Laboratories.

3. Results

The heat-flux distributions on figure 2 correspond to the NSTTF model from SolTrace. By applying more aim points in SolTrace, the heat-flux distribution can be enhanced, therefore, providing a more monotonic temperature distribution on the surface.

Nine cases were analyzed for three geometries having different offsets (fig. 1) and varying the flux levels. The idea behind having offsets was to increase the efficiency by capture of radiation from adjacent surfaces. Figures 3a and 3b show the thermal efficiency and the corresponding radiative and convective losses for each case. Several things can be concluded from these results:

1. From figure 3, even though the outlet temperature was kept constant by increasing the mass flow rate proportionally to the heat flux applied, the wall-temperature difference increases due to the increase in heat transfer rate. It is important to consider a thermal-structural analysis to ensure the mechanical stability of the receiver.
2. Radiative losses account for approximately 10-19% while convective losses account for approximately 1-10% of the total heat transfer as observed on figures 3a and 3b respectively.
3. Efficiencies above 85 % were observed in concentrations ~1000 kW/m^2. Although these concentrations are achievable, most likely they will yield temperatures above the temperature limits at the current high pressures. Therefore, an optimal peak flux must be determined.

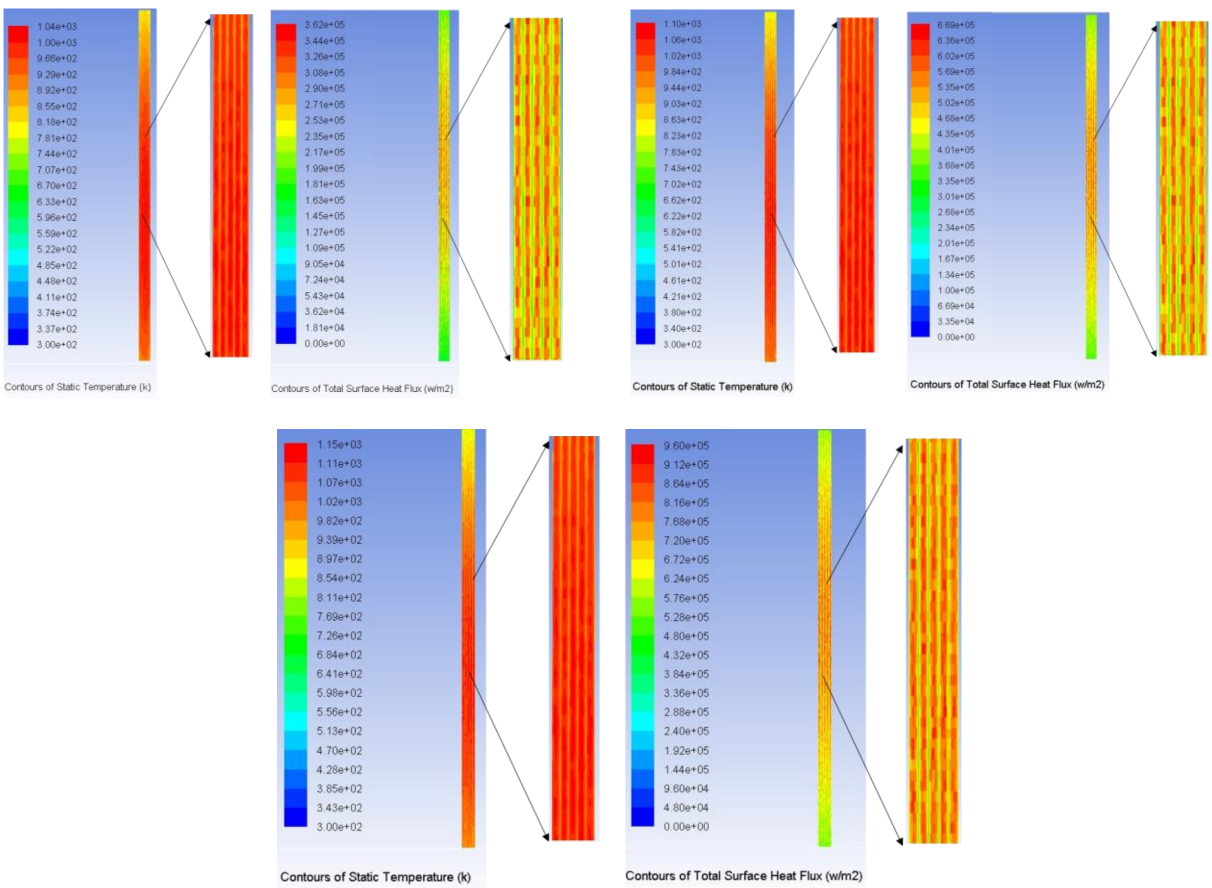

Figure 2. Temperature and heat flux contours of the cases in table 1 corresponding to a 0 degree offset and a) ~400 kW/m^2, a) ~700 kW/m^2 and a) ~1000 kW/m^2

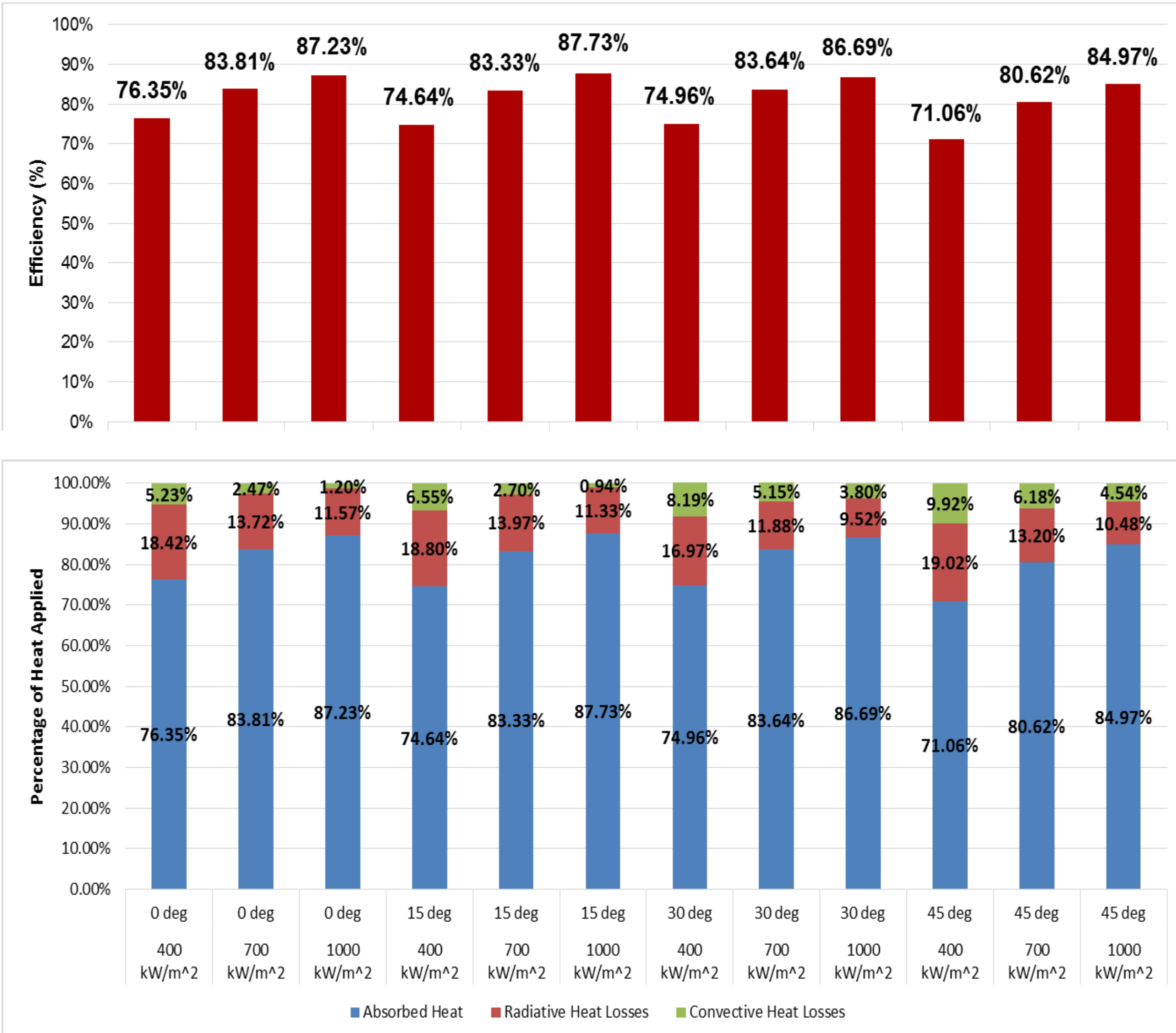

Figure 3. a) Thermal Efficiencies of the nine cases and b) Heat losses of the nine cases

For 0 degree offset with DNI of 1000 W/m2, a case with constant heat flux instead of the non-uniform distribution from SolTrace was simulated. The total power input was specified to be same, but the value of peak flux intensity was only about 40 % in the uniform distribution case in comparison to the non-uniform distribution case from SolTrace.

The predicted efficiency was higher in the case of the uniform flux distribution case by only 0.5 %. An important observation was that the predicted peak temperature on the uniformly heated walls was 1087 K, while in the case of actual heat flux distribution from SolTrace, it was 1153 K. In different conditions, the need to map actual heat flux instead of using a constant heat flux approximation might be even more significant if an accurate prediction of the temperature distribution is desired.

The design requirements have been divided into five main categories. The following are some requirements listed in 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 arrest 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 a few 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 s-CO_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 s-CO_2.

- The receiver material should not react with s-CO_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 s-CO_2 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.

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 s-CO_2 should have a guided path so as to recapture it or allow it to escape safely to environment.

4. Conclusions

1) A coupled optical-fluid-thermal model was developed using SolTrace and FLUENT to evaluate the thermal efficiency of the tubes of a tubular receiver. This is the first time a SolTrace-FLUENT coupling method is used to evaluate the efficiency of a solar thermal receiver.
   Three major conclusions could be made from this work.
   - An s-CO_2 tubular receiver intended for use in a solar power tower has been modeled using computational fluid dynamics coupled with a ray tracing software.

- The effect of mass flow rate and geometric parameters on the receiver efficiency and peak temperatures has been investigated.
- The use of actual heat flux distribution profile, rather than the constant heat flux distribution approximation was successful. This optical coupling is expected to be used in the future to predict the performance of the receiver with higher accuracy owing to the more representative heat flux profiles on the tube surfaces.

2) 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 s-CO_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 s-CO_2 receivers.
3) Modeling strategies, guidelines and input parameters required in computational fluid dynamics and structural analyses of s-CO_2 receivers utilizing ANSYS Fluent, ANSYS Mechanical, and nCode Design Life have been discussed.
4) Various subsets of requirements for design, development and testing a s-CO_2 receiver have been presented in this work. More detailed examples and guidelines will be available soon in the interim Sandia design requirements report.

5. Presentations and Publications Made or Anticipated in Future

1) 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 CO_2 Brayton Cycle*, Proceedings of the 9th International Conference on Energy Sustainability (ES2015), San Diego, CA, June 28th – July 2nd, 2015. (SUBMITTED)

2) J. D. Ortega, S. D. Khivsara, J. M. Christian, C. K. Ho, *Design Requirements For Direct Supercritical Carbon Dioxide Receiver Development And Testing*, Proceedings of the 9th International Conference on Energy Sustainability (ES2015), San Diego, CA, June 28th – July 2nd, 2015. (SUBMITTED)

6. Next Steps & Follow up of Work

Along with Dr. Cliff Ho (SNL) and Prof. Pradip Dutta and Dr. Vinod Srinivasan (both from IISc, visited SNL in Nov. 2014) a proposal (concept paper) for the DOE CSP APOLLO funding opportunity was drafted and has been submitted. At the concept paper stage of the proposal, we described a novel volumetric s-CO_2 receiver design with short-term integrated storage. The paper also identifies the anticipated impact, technical risks/issues and other challenges for the proposed design. The concept paper has been encouraged by DOE and the full proposal is now under preparation

With the new techniques developed along with the team at Sandia National Labs, more accurate and realistic simulations of the receiver designs that are under study in SERIIUS CSP 1 and CSP Core 2 have now been undertaken. The plans for prototyping and testing of the receivers being developed by the teams of SNL, IISc and IIT Bombay have been discussed and details for execution are now underway.

7. Acknowledgements

I would like to thank the management of SERIIUS and MAGEEP for providing me this opportunity to undertake research at Sandia National Laboratories. I would also like to thank my Ph.D. advisors at IISc, Dr. Pradip Dutta and Dr. Vinod Srinivasan.

It was a pleasure working with SERIIUS members Dr. Cliff Ho, Dr. Subhash Shinde, Josh Christian, Jesus Ortega, and everyone else at the NSTTF! The visit was an enriching experience and enhanced my knowledge in the field of solar thermal technologies. I would also like to acknowledge the inputs from Dr. Antoine Boubault and David Romano, who were fellow visiting scholars at Sandia National Laboratories.

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