SAND2018-0348R

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U.S. DEPARTMENT OF ENERGY

Project Accomplishment Summary

Sandia National Laboratories
Operated for the U.S. Department of Energy by
Sandia Corporation
Albuquerque, New Mexico

PROJECT ACCOMPLISHMENTS SUMMARY

Cooperative Research and Development Agreement (#SC14/01811.02.00)
between **Sandia National Laboratories** and
Commonwealth Scientific and Industrial Research Organisation

Note: This Project Accomplishments Summary will serve to meet the requirements for a final abstract and final report as specified in Article XI of the CRADA.

Title: Solar Driven Supercritical CO_2 Brayton Cycle Testing (CSP)

Final Abstract:

Sandia National Laboratories (SNL) provided design, modeling, and analysis to support Commonwealth Scientific and Industrial Research Organisation's (CSIRO's) efforts to develop a receiver system for solarized supercritical CO_2 (sCO2) Brayton cycles. A solarized sCO2 power cycle is being pursued by both the U.S. DOE and the Australian government as a means to enable renewable, dispatchable electricity with low costs and high efficiency, which will improve reliability and resiliency of both nations' energy grids. Results of this work provided annualized thermal efficiencies for an intermediate-scale falling particle receiver that can be used as the basis for a direct sCO2 receiver design that is being pursued by CSIRO. In addition, different particle-receiver configurations were analyzed to investigate large-scale designs up to ~100 MW_e.

Background:

SNL and CSIRO were both pursuing solar-driven supercritical CO_2 Brayton cycles. The current state-of-the-art was coal-fired steam Rankine power cycles, which can only reach ~40% thermal-to-electric efficiency. In contrast, sCO2 cycles can reach 50% efficiency, and solarized sCO2 cycles can provide clean, dispatchable power with thermal energy storage. sCO_2 power cycles offer the potential for better overall plant economics than steam turbines, primarily due to a higher power conversion efficiency, more compact size, and reduced capital cost. Because of this promise, the U.S. DOE and other organizations have been actively investigating sCO_2 systems for use in next-generation nuclear power, concentrated solar power (CSP), geothermal, and fossil energy systems.

SNL has led the power cycle hardware development effort under the DOE Nuclear Energy program. Similarly, CSIRO has been actively pursuing the sCO_2 cycle for CSP applications through advanced receiver design and associated power technology for high efficiency solar thermal power. This project aimed to join the different strengths of the two parties, SNL and CSIRO, in order to further the state of research into high efficiency solar energy systems. Due to an ongoing sCO_2 power cycle hardware development program, SNL has one-of-a-kind facilities and infrastructure, and SNL personnel have a unique understanding of Brayton cycle operations and concentrating solar power. CSIRO has a wealth of experience in concentrated solar power technology, including receiver design and power cycle analysis.

This partnership between federal research agencies of the U.S. and Australia builds upon a cooperation between the U.S. Department of Energy and the Australian Renewable Energy Agency. It reflected a mutual need to accelerate the transition to a clean renewable energy economy, while enhancing energy security, addressing climate change, and supporting sustainable economic growth.

Description:

SNL and CSIRO worked together to develop the requirements and boundary conditions for an intermediate scale particle receiver that could be used for comparison against the direct sCO2 receiver that CSIRO was designing. SNL then led the development and analysis of a 50 $\mathrm{MW_e}$ particle receiver with the objective of obtaining annual thermal efficiencies. In addition, SNL investigated the thermal solar-to-thermal efficiency and tower height for alternative particle receiver configurations (single cavity/polar field vs. four cavity/surround field) for larger-scale systems. The following sections summarize these efforts.

A computational fluid dynamics model of a 50 MWe falling particle receiver was developed to evaluate the ability of this receiver concept to scale to intermediate sized systems while maintaining high thermal efficiencies (Figure 1). A compatible heliostat field for the receiver was generated using NREL's SolarPILOT, and this field was used to calculate the irradiance on the receiver at seventeen different dates and times throughout the year. The thermal efficiency of the receiver was evaluated at these seventeen different samples using the computational fluid dynamics (CFD) model and found to vary from 83.0 – 86.6% for particle mass flow rates varying from 25.7 – 36.6 kg/m·s and average particle outlet temperatures 750 – 775°C (Figure 2). The annualized thermal efficiency was calculated from the samples to be 85.7%. Finally, a table was generated that summarized this study along with other similar CFD studies on falling particle receivers over a wide ranges of scales (Table 1).

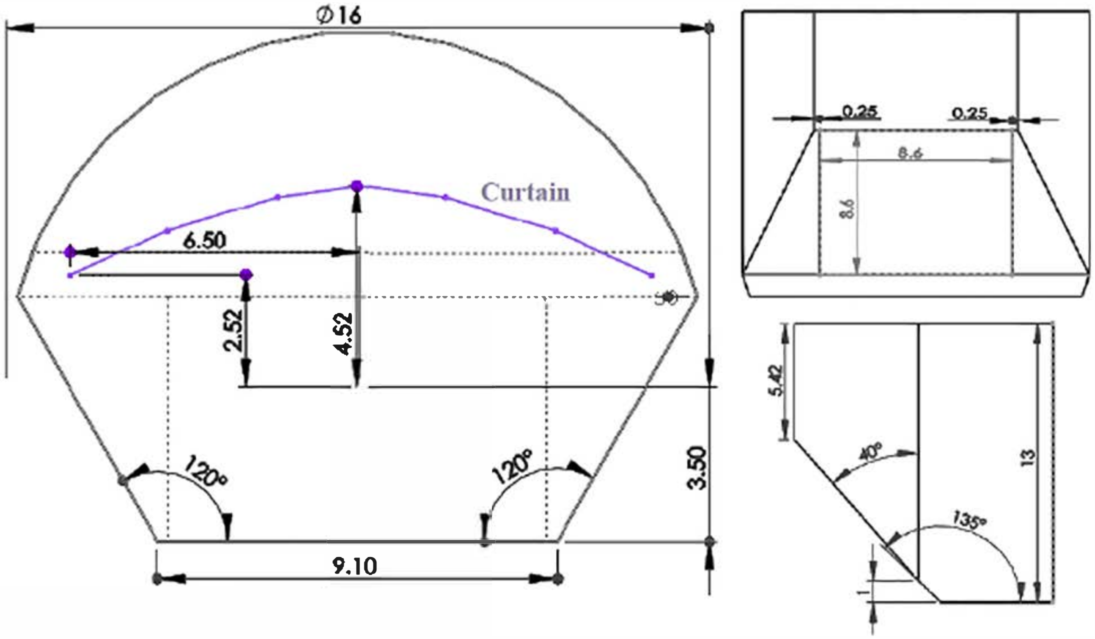
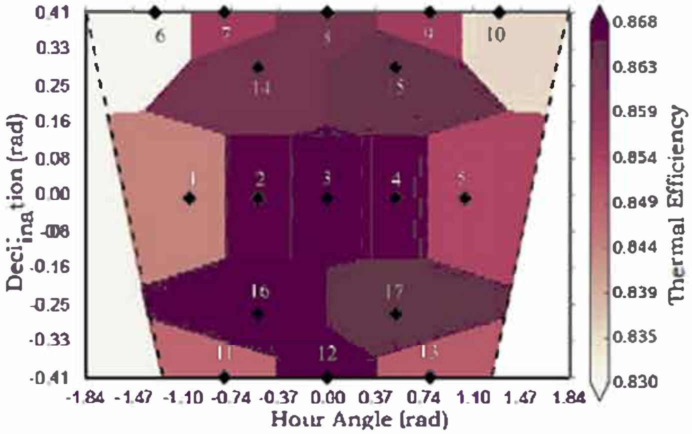


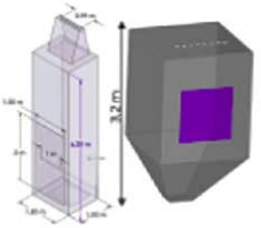
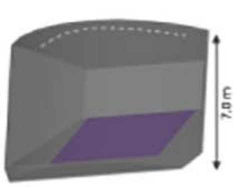
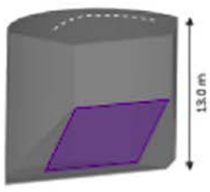
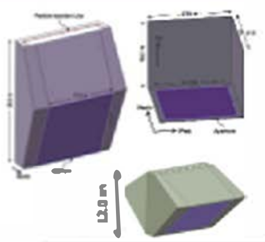
Figure 1. Drawing of the proposed falling particle receiver viewed from the top (left image) from the side (bottom right image) and the front (top right image). Units in meters



1.	Equinox:	-4 hrs.
2.	Equinox:	-2 hrs.
3.	Equinox:	solar noon
4.	Equinox:	+2 hrs.
5.	Equinox:	+4 hrs.
6.	Summer solstice:	-5 hrs.
7.	Summer solstice:	-3 hrs.
8.	Summer solstice:	solar noon
9.	Summer solstice:	+3 hrs.
10.	Summer solstice:	+5 hrs.
11.	Winter solstice:	-3 hrs.
12.	Winter solstice:	solar noon
13.	Winter solstice:	+3 hrs.
14.	May 6:	-2 hrs.
15.	May 6:	+2 hrs.
16.	November 1:	-2 hrs.
17.	November 1:	+2 hrs.

Figure 2. Map of the recediver thermal efficiency at seventeen weighted dates and times for an annualized thermal efficiency of 85.7%

Table 1. Summary table of falling particle receiver studies at different scales

Falling Particle Receiver Models at Various Scales	1-2.5 MW$_{th}$	10 MWe	50 MWe	100 MWe
				
Reported Efficiencies	~35% - 53% [7], 44.7% - 52.9% [15,16], 86.3% - 89.5% [14]	70.1% - 87.0% Annual value: 85.0%	83.0% - 86.8% Annual value: 85.7%	North-Facing: 72.3% [8], 69.7% - 86.8% [6]; Face Down: 78.9% [8]
Model Description	A coupled Lagrangian-Eulerian CFD model is used to predict the behavior of the particles as they fall through the air in the receiver cavity. Incident radiation from the solar field is included via a non-grey discrete ordinates radiation model. Losses from the receiver include exterior convection, radiative losses from reflections or thermal emissions, and convective losses from the particles to the air.			
Notable Features	• Aperture: 3.0 x 1.0 m; 1.0 x 1.0 m • Nod angle: 0° • Validated w/ low temp. data [7] • More prototypical design [14] • Investigated novel particle curtain release patterns [14-16] • D_{part} = 280 – 697 µm • Design tested at NSTTF [5]	• Aperture: 5.6 x 5.6 m • Nod angle: 50° • Curved particle curtain, 7.89 m • NREL's SolarPILOT used to generate compatible solar field • D_{part} = 697 µm • Heliostat #: 640 • Eff. evaluated over calendar year	• Aperture: 8.6 x 8.6 m • Nod angle: 40° • Curved particle curtain, 13.95 m • NREL's SolarPILOT used to generate compatible solar field • D_{part} = 500 – 697 µm • Heliostat #: 2,529 • Eff. evaluated over calendar year	• Investigated North-Facing (NF) and Face Down (FD) designs [8] • Aperture: NF: 10.6 x 10.6 m - 17.0 x 17.0 m; FD: 18.0 x 18.0 m • NF Nod angle: 20° - 50° • Investigated particle recirculation • D_{part} = 697 µm • Heliostat #: 3,242 – 7,183
Sources	[5], [7], [14], [15], [16]	[17]	-	[6], [8]

Several system layout options have been considered for the falling-particle system, which requires a cavity receiver. The first option is a polar field and single cavity. Concerns were raised over the distance of the farthest heliostats with a 100-MW$_e$ field (550-MW$_{th}$ with solar multiple = 2.4 and 10–15 hours of storage), so a surround field with four cavities was also considered. Both of these options were compared using NREL's SolarPilot optical performance software to a traditional external cylindrical receiver, such as that used for molten-salt systems, with consistent inlet and outlet temperatures, heat losses, and peak surface temperature.

The cavity receivers were modeled with a single aim-point at the center to maximize the concentration ratio. The heliostats were 144 m^2 with a surface slope error of 1.53 mrad. The losses were fixed at 60 kW/m^2, accounting for re-radiation and convection estimated for a 750°C heat-transfer fluid (HTF) outlet temperature, or 800°C metal surface maximum temperature, with an inlet temperature of 550°C. The area for losses was based on the surface area for an external cylindrical receiver, and the aperture area for the cavities, and an average absorptivity/emissivity across the area was set to 94% in all cases. The total thermal input to the HTF, after losses, was 550 MW_{th} at design.

The cavity shape was square, tilted down at 15 degrees, and the size optimized for each plant size. In the 4-cavity configuration, each cavity was identical (i.e., one aperture size was used regardless of position). The aperture size, tower height, and field size for both the 4-cavity and single-cavity models were optimized for best combined optical and thermal performance, but not for cost. The external receiver was optimized with a maximum flux of 1,000 suns, resulting in a 12.3-m high, 28.8-m diameter receiver.

The 4-cavity approach under-performed the external receiver in all sizes studied, primarily due to increased spillage losses. The optimum size cavity was slightly larger in total area than the optimized external receiver in each case in order to balance spillage and re-radiation. Not all variables were exercised in this study, and the results should be indicative but not definitive. Figure 3 shows the optical to thermal performance at the equinox at solar noon.

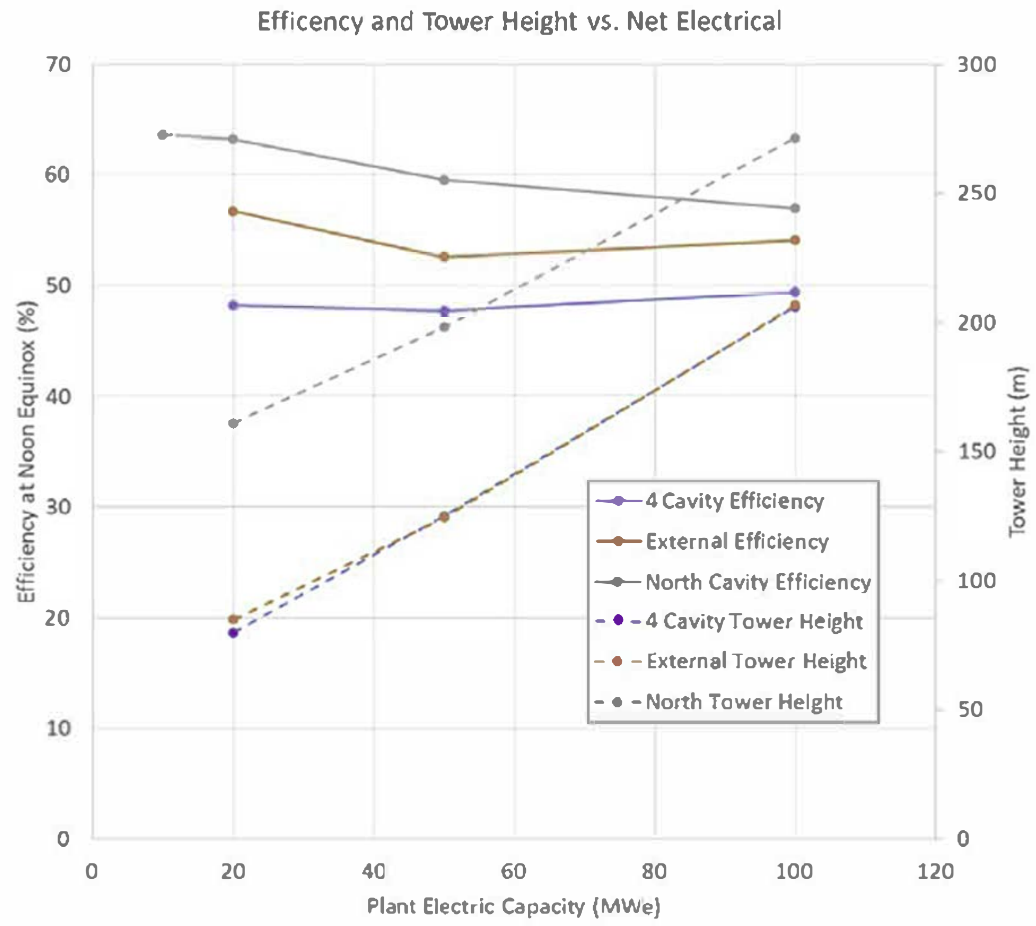


Figure 3. Cavity optical/thermal efficiency performance compared to a generic external receiver with consistent inlet and outlet temperatures, heat losses, and peak surface temperature.

The single-cavity performance was superior at all scales, even with the 100-MW$_e$ case, in which the farthest heliostats are 3.5 km from the tower. The aperture size was only slightly larger than the aperture of each of the four cavities, because the aim-point is centered and the only increase was due to sunshape-spreading of the reflected beam. This substantially reduces the re-radiation loss compared to the 4-cavity model and the external receiver. In addition, the optical performance of the north field is substantially better than the surround field—both instantaneous at the equinox noon case and for annual performance. The aperture is about 30 m across for the north field at 550 MW$_{th}$ design.

The downward trend of the north cavity case with system size reflects the extreme distances to the tower from the outer heliostats, but even at the largest scales, it does not offset the gains in reduced losses with the cavity The peak flux at the aperture of the single cavity is 7000 suns, with an average flux across the aperture of 676 suns. The annual solar-to-thermal efficiency (Thermal energy into HTF/(Time × DNI × glass area summed for entire year)) for the north cavity on the 100-MW$_e$ plant was 53%, compared to 45% for an external receiver and surround field, as determined in SAM using Barstow weather data.

This simplified study helps to emphasize the performance gains that can be realized with the falling-particle system, incorporating a cavity receiver and with the potential for high flux absorptance within the receiver. Further, it points future development toward a single cavity polar-directional receiver rather than multiple cavities with a surround field. Future systems modeling should be done to account for actual cavity shape to more accurately represent view factors and losses, both radiative and convective, to confirm these results and guide cavity development.

Benefits to the Department of Energy:

~~This work and collaboration~~ enables the advancement of solarized supercritical CO_2 power cycles, which is an important area of research funded across multiple offices within DOE (EERE, FE, NE). This renewable energy technology addresses one of DOE's critical missions to deploy technologies that enable secure and resilient energy supplies for the nation.

This work has been published in publicly available documents:

- Mills, B. and C.K. Ho, Proceedings of the SolarPACES 2017 Conference, Santiago, Chile, September 2017,
- Mehos et al., 2017, Concentrating Solar Power Gen3 Demonstration Roadmap, National Renewable Energy Laboratory Technical Report, NREL/TP-5500-67464.

Economic Impact:

This work will enable CSIRO and other companies to better design and implement receivers for solarized sCO2 Brayton systems. It complements DOE's recent ~$85M investment in the development of a 10 MW$_e$ sCO2 Brayton cycle test loop. This project provides critical information that will assist the solarization of the Brayton cycle. It is believed that the combined work will enable commercial deployment of solarized sCO2 Brayton systems within 5 – 10 years with industrial revenue of hundreds of millions of dollars.

Project Status:

This project has been completed. The results will support upcoming proposals from DOE and the Australian government.

ADDITIONAL INFORMATION

Laboratory/Department of Energy Facility Point of Contact for Information on Project

Dr. Clifford K. Ho
Distinguished Member of the Technical Staff
Sandia National Laboratories
Albuquerque, NM 87185
(505) 844-2384
ckho@sandiagov

Company Size and Points of Contact

CSIRO
Dr. Jin-Soo Kim
Jin-Soo.Kim@csiro.au

CRADA Intellectual Property

N/A

Technology Commercialization

N/A

Project Examples

N/A

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This summary has been approved for public release by Sandia and Commonwealth Scientific and Industrial Research Organisation (CSIRO).

Sandia National Laboratories

12/13/17

By Clifford K. Ho

12/13/17

Clifford Ho
Principal Investigator

Date

Sandia National Laboratories

By
Manager
WFO/CRADA Agreements

12/12/17
Date

Commonwealth Scientific and Industrial Research Organisation (CSIRO)

By 12/20/17
Title: Project Leader
Principal Research Scientist
Date

In order to expedite the process, if we do not receive your signed reply by 12/22/17 we will assume your concurrence for the release of this document to the public.