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Fractal-Like Receiver Geometries and Features for Increased Light Trapping and Thermal Efficiency

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Abstract. Novel designs to increase light trapping and thermal efficiency of concentrating solar receivers at multiple length scales have been conceived and tested. The fractal-like geometries and features are introduced at both macro (meters) and meso (millimeters to centimeters) scales. Advantages include increased solar absorptance, reduced thermal emittance, and increased thermal efficiency. Radial and linear structures at the meso (tube shape and geometry) and macro (total receiver geometry and configuration) scales redirect reflected solar radiation toward the interior of the receiver for increased absorptance. Hotter regions within the interior of the receiver can reduce thermal emittance due to reduced local view factors to the environment, and higher concentration ratios can be employed with similar surface irradiances to reduce the effective optical aperture, footprint, and thermal losses. Coupled optical/fluid/thermal models have been developed to evaluate the performance of these designs relative to conventional designs, and meso-scale tests have been performed. Results show that fractal-like structures and geometries can increase the thermal efficiency by several percentage points at both the meso and macro scales, depending on factors such as intrinsic absorptance. The impact was more pronounced for materials with lower intrinsic solar absorptances (<0.9). The goal of this work is to increase the effective solar absorptance of oxidized substrate materials from ~0.9 to 0.95 or greater using these fractal-like geometries without the need for coatings.

INTRODUCTION

Conventional concentrating solar power receivers consist of panels of tubes arranged in a cylindrical or cubical shape, but these configurations also maximize radiative and convective heat losses to the environment; sunlight reflected off of these surfaces is lost to the environment. To increase the receiver thermal efficiency, previous research has focused on the development of solar selective coatings that increase solar absorptivity and reduce thermal emissivity. However, most of these coatings have been shown to suffer from degradation that reduces the lifetime performance of the plant and increases costs associated with reapplication [1]. In this work, we develop fractal-like receiver designs employing light-trapping structures and geometries at multiple length scales to increase the effective solar absorptance and efficiency of high-temperature receivers without the need for coatings.

Several previous researchers have looked at novel features or geometries to increase light trapping. Garbrecht et al. [2] evaluated pyramid shape receiver structures for molten salt power tower use. The pyramid structures extended from the base of the receiver, and the peaks faced the incoming solar radiation. It was shown that reflected losses could be reduced by 1.3% and thermal emission losses were reduced by 2.8%. The difficulty with these structures was achieving fluid flow within the peaks of the pyramids, and very hot spots developed at these locations. Another recent work considering fin structures within a parabolic trough receiver envelope was developed by Kasperski, et. al. [3]. This work showed that fin structures within the envelop cavity could increase efficiency by 13%. The National Renewable Energy Laboratory developed a super-critical CO_2 receiver design that takes advantage of alternative receiver geometries to increase light trapping and efficiency. They showed that a 92% efficiency can be achieved with a horizontal bladed receiver design, [4] which is also described by a Sandia patent application. [5] While these previous studies evaluated features and geometries at a single scale, the current work looks to develop novel features and geometries across multiple length scales to further increase light trapping and thermal efficiencies.

APPROACH

Examples of fractal-like receiver designs employing light-trapping structures and geometries at multiple length scales can be seen in **FIGURE 1**. Radial and linear structures at the meso scale (tube shape and geometry) and macro scale (total receiver geometry and configuration) redirect reflected solar radiation toward the interior of the receiver for increased light trapping and absorptance, which is in contrast to cylindrical and cubical shapes that reflect any incoming light back to the environment. Light-trapping features and texturing can also be applied at the micro scale (i.e., on the surface of the meso-scale tubes). A great deal of research already exists with the aim of developing high-temperature coatings, but this work focuses on fractal-like geometries at the meso and macro scales to achieve high efficiencies without the need for coatings. These fractal-like receivers can utilize conventional heat transfer fluids (e.g., molten salt and steam) used in CSP plants, but can also utilize super-critical CO_2 for increased power block efficiency, depending on specific designs and resulting allowable stresses. Structural analyses have been performed on these geometries for various pressure loads and thermal gradients to determine acceptable designs for prescribed operating conditions.

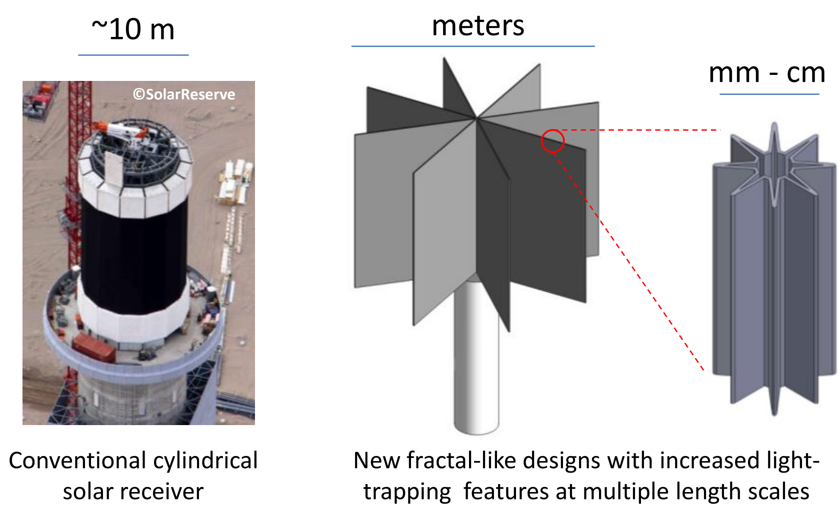


FIGURE 1. Conventional design (left) and examples of fractal-like designs and structures for solar thermal receivers to enhance solar absorptance at multiple length scales (provisional patents 61/901628 and 62/015052 [5, 6]).

Different designs for these light-trapping structures and geometries are shown in **FIGURE 2**. The macro-scale fractal-like receiver designs can accommodate both surround and directional (e.g., south-facing) heliostat fields. The designs can incorporate hat-like features to reduce radiative and convective losses from the top of the receiver, and the linear patterns can be oriented either vertically or horizontally. The linear panels (bottom left image in **FIGURE 2**) can also be placed side-by-side in a cylindrical pattern to accommodate a surround heliostat field. The meso-scale, fluid-carrying tubes employ similar features and geometries to trap the light and increase solar absorptance as shown in **FIGURE 2**. The tubes can be placed side-by-side or in various configurations to form the panels of tubes shown in the macro-scale designs. Additive manufacturing methods such as 3D printing, laser engineered net shaping, and powder bed fusion techniques can be used to fabricate the meso-scale tube structures. Filleted or rounded structures may be needed to reduce stress from thermal gradients and/or high internal fluid pressures. Optimization of these designs based on optical/thermal/fluid/structural analyses will be performed for full receiver panels composed of these alternative tube geometries.

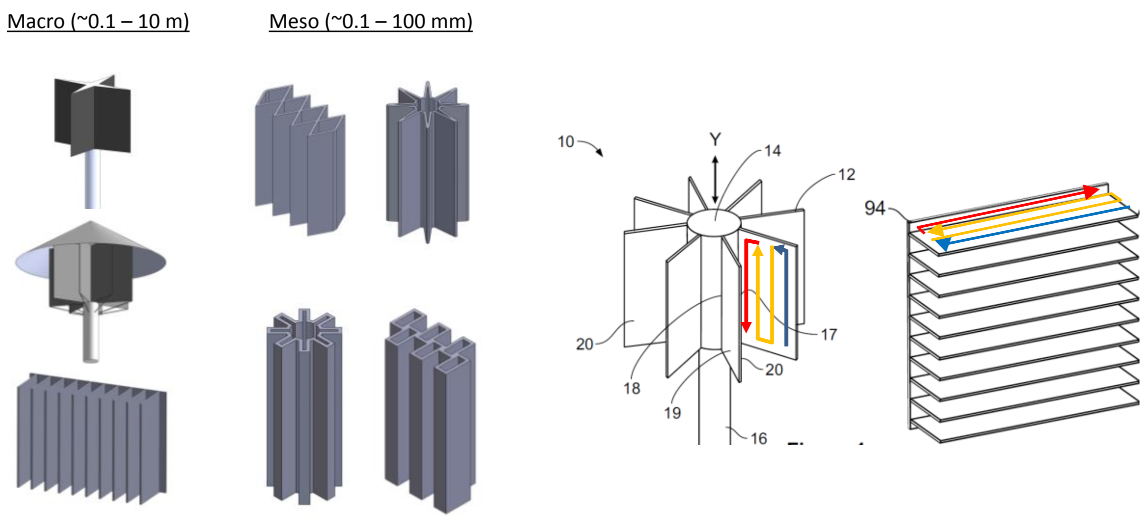


FIGURE 2. Left: examples of fractal-like receiver designs at the macro and meso scales. Right: direction of fluid flow in macro-scale designs (provisional patents 61/901628 and 62/015052 [5, 6]).

MODELING

Optical Modeling

The concentrated solar radiation incident upon the receiver can be modeled using ray tracing, cone optics, or other analytical methods.[7] Yellowhair et al.[7] concluded that ray tracing was most suitable for modeling complex receiver geometries such as those presented in this paper. The code SolTrace[8], a free ray-tracing tool customized for optical modeling of concentrating solar power systems, was benchmarked against other optical tools[7] and selected for use in this study. A postprocessor was written in Matlab to import flux patterns from SolTrace into a file that could be read and applied as boundary conditions by ANSYS Fluent, a computational fluid dynamics software that can simulate thermal losses by radiative emittance and convection, heat absorption, and temperature distributions. Other analytical tools built into ANSYS Fluent (discrete ordinates radiation model) and Solidworks Flow Simulation were also used for thermal/fluid modeling. The use of these coupled optical/thermal/fluid models is advantageous when modeling complex geometries with large spatial scales.

Meso-Scale Modeling

Flat and vertically finned meso-scale structures were modeled to evaluate the potential enhancement of solar absorptance by surface features and structures. These meso-scale designs are intended to represent sections of non-conventional pipe geometries that can be used to carry the heat-transfer fluid while increasing the effective solar absorptance of the pipes with light-trapping structures at the meso-scale. Each piece is hollow with a wall thickness of 1 mm. The thermal properties of the substrate were assumed to be those of stainless steel 316 while the radiative surface properties are varied (e.g., solar absorptance varied from 0.5 – 0.95 assuming a gray surface). A solar irradiance of 100 W/cm^2 (~1000 suns) was directed toward one side of each sample while the interior walls of each sample were maintained at 500 °C (average receiver temperature) to simulate a heat sink caused by the heat-transfer fluid. Half symmetry was employed so that only the right half of the samples were simulated. A grid convergence was performed, and over 1 million cells were used in each simulation. Radiation (solar and thermal), natural convection, and conduction through the walls were included in the models. The radiation model employs the discrete transfer (ray-tracing) method and assumes diffuse, gray-body radiation between surfaces.

Results show that while the finned geometry increased the amount of convective and thermal radiative heat loss due to the larger surface area, the solar reflected loss was significantly lower (30 – 40%), resulting in a lower total heat loss (7 – 26%). In addition, at lower material absorptances, the reduction in total heat loss was more pronounced. At higher material absorptances, the reduction in total heat loss was less. This indicates that if a receiver coating can maintain a high solar absorptance (~0.95), the use of flat or conventional shapes may be suitable. However, if the coating degrades below ~90% solar absorptance, the proposed fractal-like structures can increase the effective solar absorptance significantly. **FIGURE 3** shows the thermal efficiency (net absorbed power divided by the incident power) and the increase in effective absorptance (absorbed solar power (neglecting convective and thermal radiative losses) divided by the incident power), which reflects this trend as a function of prescribed material absorptance. At a material solar absorptance of 0.95, the thermal efficiency of the flat and finned geometries are nearly the same, but if the material solar absorptance decreases to 0.9, the finned structure can increase the thermal efficiency by several percent. At a material solar absorptance of 0.7, the finned structure increases the thermal efficiency by 13%. Therefore, employing fractal-like designs and structures using plain substrate materials may be suitable in some cases without the need for coatings.

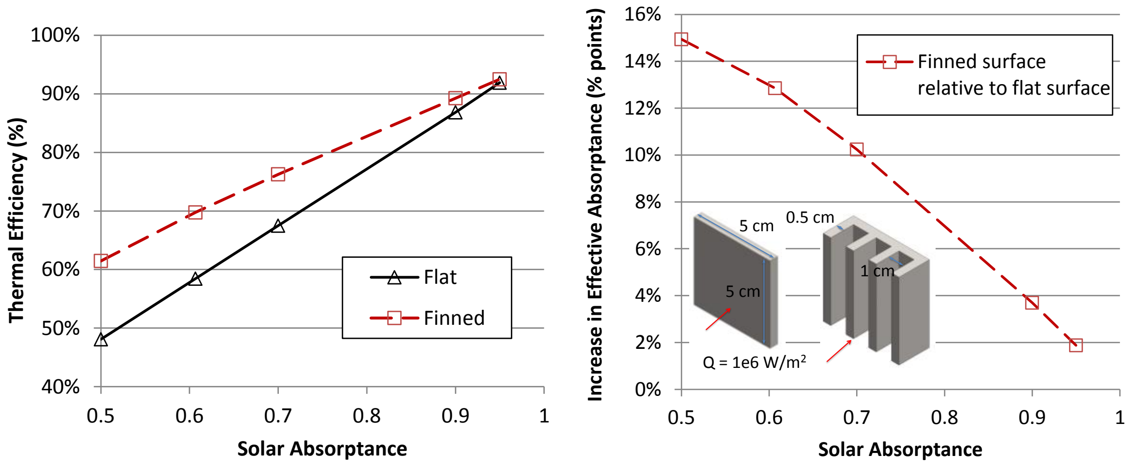


FIGURE 3. Simulated efficiency and increase in effective absorptance as a function of intrinsic material solar absorptance for flat and finned meso-scale geometries.

Simulations of different offsets and orientations of tubular geometries revealed that the effective solar absorptivity increased as the offset angle increased for circular, square, and rectangular tubes due to increased light trapping (Figure 4). For the diamond geometry, the effective solar absorptivity decreased as the offset angle increased. Simulations of different orientations of the tubular geometries showed that the effective solar absorptance can either increase or decrease as a function of orientation based on the available irradiated area and reflective losses (less light trapping).

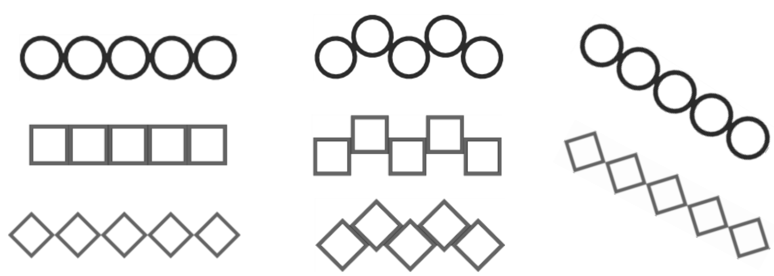


Figure 4. Examples of different meso-scale geometries, offsets, and orientations that were simulated.

ANSYS Mechanical was used to evaluate stress distributions within the tubes under expected thermal and mechanical loads. As expected, the stress levels at the corners of the rectangular and diamond tubes were higher than the circular tubes and exceeded allowable stress levels for high-pressure supercritical carbon dioxide operating conditions (20 MPa, 700 °C). An evaluation of the allowable stresses for molten-salt and supercritical carbon dioxide working fluids is summarized in Ortega et al.[9] Rounded corners and increased tube thickness reduced the stress levels. Optimization of the tubular designs that satisfy both optical and structural requirements is ongoing.

Macro-Scale Modeling

Four macro-scale fractal-like receiver configurations were modeled: flat (reference case), radial panels, horizontal louvered panels, and vertical panels.[10] The thermal efficiency, convective heat loss patterns, and air flow around each receiver design were simulated using ANSYS FLUENT. Simulated results of alternative macro-scale geometries show that thermal efficiencies were increased by nearly 5% with radial or linear bladed receiver configurations (**FIGURE 5**). The horizontal louvered design was best, followed by the vertical and radial panel designs. Radiative losses were reduced with the fractal-like geometries due to reduced local radiative view factors in the hottest interior regions of the receiver. Convective losses were slightly higher in the vertical panel configurations, while convective heat losses were reduced in the horizontal louvered panel configuration. With the horizontal louvered configuration, convective heat losses from the hot interior regions of the receiver can be recuperated in cooler regions, thereby reducing the overall convective heat loss.[11]

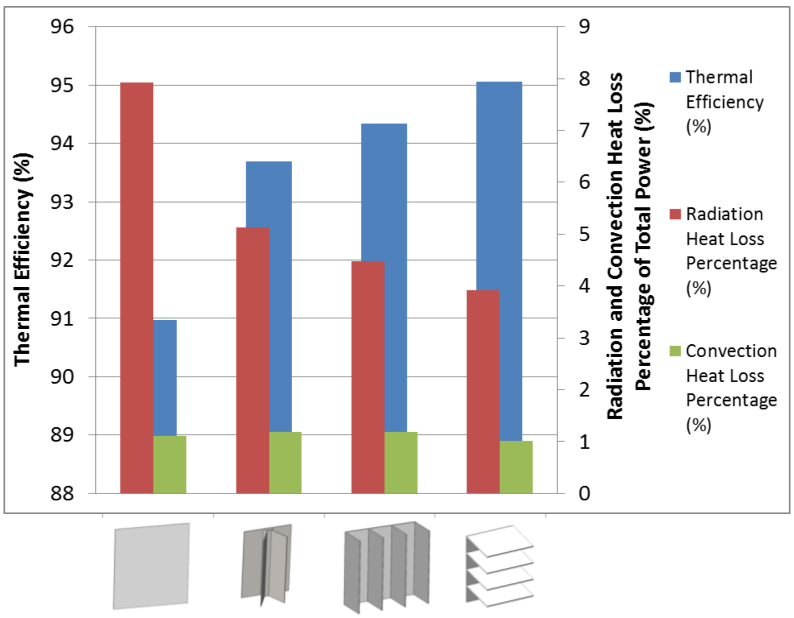


FIGURE 5. Thermal efficiency and heat losses for alternative macro-scale receiver geometrie with an average irradiance of 500 kW/m^2.[10]

TESTING

The solar furnace facility at Sandia's National Solar Thermal Test Facility (NSTTF) can provide 16 kW thermal power and up to 600 W/cm^2 peak irradiance over a 5 cm spot size. The solar furnace consists of a sun-tracking heliostat (95 m^2) which directs the sunlight towards a fixed dish concentrator (6.7 m diameter) housed in a building. The dish focal length is 4.1 m were the test articles are placed. Just outside the building between the heliostat and dish is a louver type attenuator system which controls the amount of light that is incident on the dish. The solar furnace facility is shown in **FIGURE 6**.

Meso-scale receiver parts with fractal-like geometries that were fabricated and tested are shown in **FIGURE 7**. The parts are 5 cm tall and were fabricated from Inconel 718 using the power-bed fusion technique. The flat plate was used as a baseline for comparison to the other geometries. Before exposing the flat part, its reflectance was measured with the Surface Optics 410-Solar reflectometer, which showed 24% reflectance (solar absorptance ~0.76). The reflectance was measured again after exposure and oxidation, which showed a reflectance of 14% (solar absorptance ~0.86). When the samples were pre-oxidized at 800 °C in an oven, the solar absorptance of oxidized Inconel 718 reached values greater than 0.9.

The receiver parts were placed, in pristine conditions (i.e., unoxidized), at the focus of the dish concentrator one part at a time. The variable attenuator was then opened to 5% and the parts were illuminated for up to two minutes until the surface temperature reached ~700°C as measured with an infrared camera. The 5% attenuator opening provided ~30 W/cm^2. Photographs of the receiver parts, using a digital camera, before and immediately after opening the attenuator and about a minute later were captured. The photographs were then analyzed with the PHLUX tool.[12]

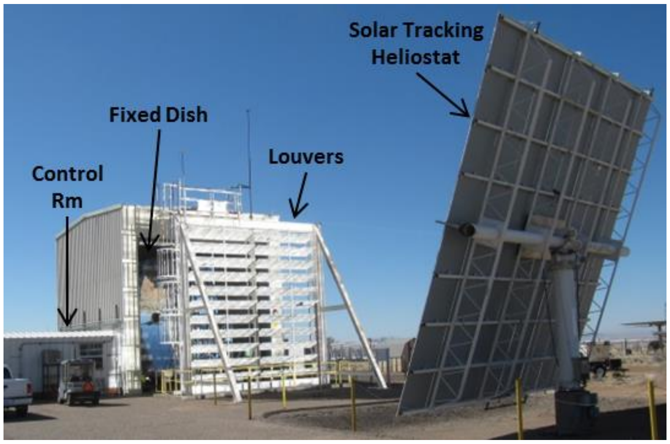
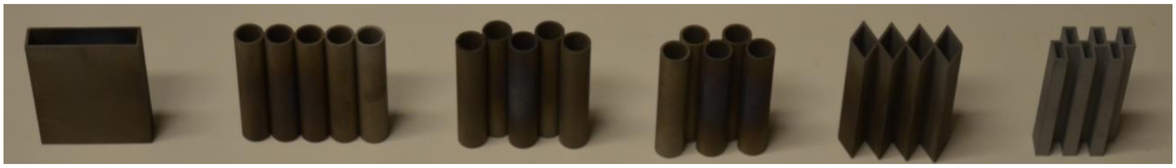


FIGURE 6. Solar furnace facility at the NSTTF that can provide 16 kW_{th} and up to 600 W/cm^2 peak flux..



Flat Plate 0° Offset Tubes 30° Offset Tubes 45° Offset Tubes Diamond Tubes Offset Rectangles

FIGURE 7. Prototype meso-scale fractal-like receiver parts fabricated with power-bed-fusion additive manufacturing using Inconel 718. The parts are all 5 cm tall and were tested on-sun in the solar furnace at ~30 W/cm^2.

Digital images were recorded and processed using the PHLUX method[12] to determine the relative irradiance distribution on each sample. These were then compared to ray-tracing simulations (**FIGURE 8**). Ray-tracing results show a similar irradiance patterns as the PHLUX processed images. The ray-tracing results show that absorptance is improved for the fractal-like geometries due to their light-trapping properties. The incident radiation was directed into the valleys of the corrugations, increasing solar absorption. The effective absorptance from each part was determined using SolTrace. The analysis was performed in two steps. The first step was to determine the total solar power incident on the receiver surfaces. This is single incidences of the solar rays on the receiver surfaces after which the rays were terminated. In the second step, the incident solar rays were allowed to reflect off the receiver surfaces multiple times. On a flat surface, the rays reflect only once and the reflected rays are lost into the atmosphere. However, for the fractal-like receiver geometries, there can be multiple reflections between the surfaces and into corrugations causing a light-trapping effect. This leads to more absorption of the incident solar radiation by the receiver surfaces. The ratio of the total absorbed solar radiation and the total incident solar radiation were taken. The results for each receiver part are shown in **FIGURE 9** for two different intrinsic material absorptances. Results show that relative to a flat plate, the new geometries could increase the effective solar absorptance from 86% to 92% for an intrinsic material absorptance of 86% (e.g., oxidized Inconel 718), and from 60% to 73% for an intrinsic material absorptance of 60% (e.g., alumina).

This significant finding shows that fractal-like receiver designs employing light-trapping structures and geometries at multiple length scales can increase the effective solar absorptance and efficiency of high temperature receivers without the need for selective absorber coatings or high-temperature paints.

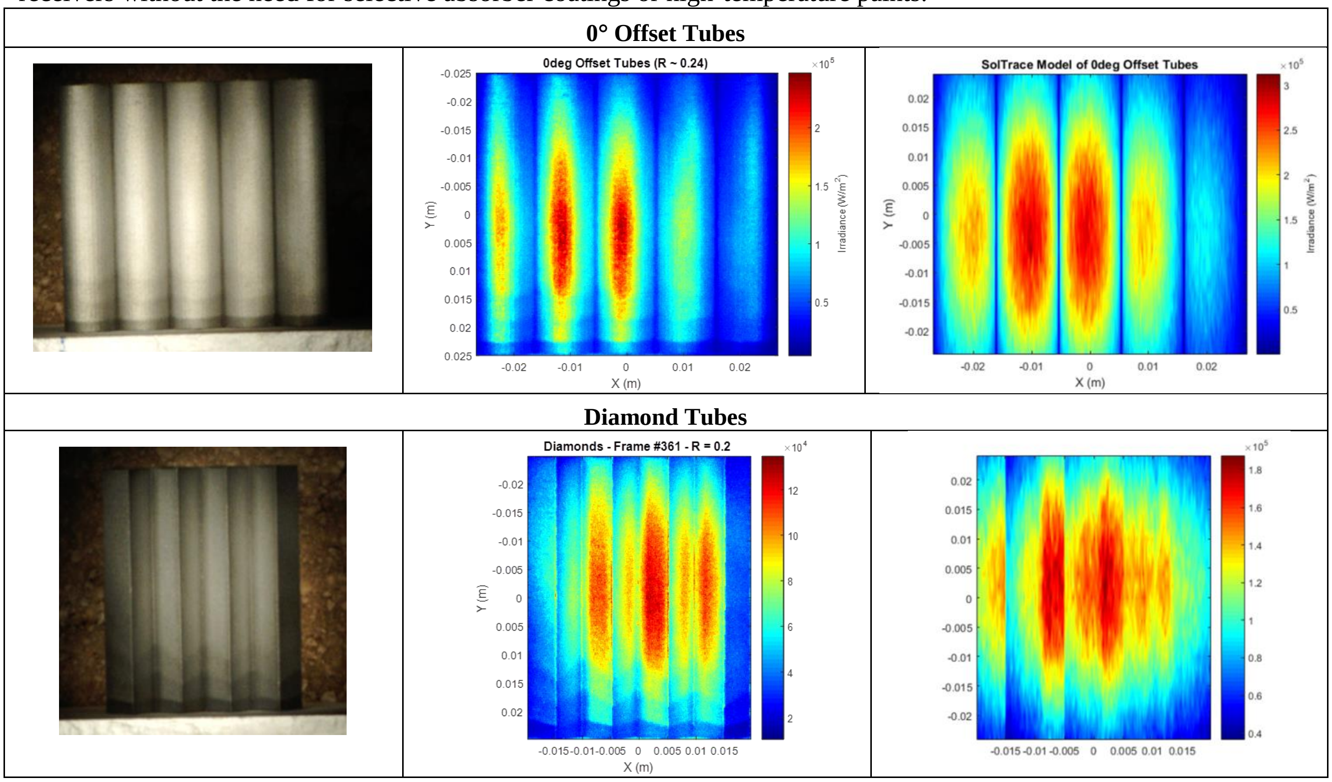


FIGURE 8. Test results showing photographs (left), irradiance measurements (middle), and model predictions (right) for three different tube configurations.

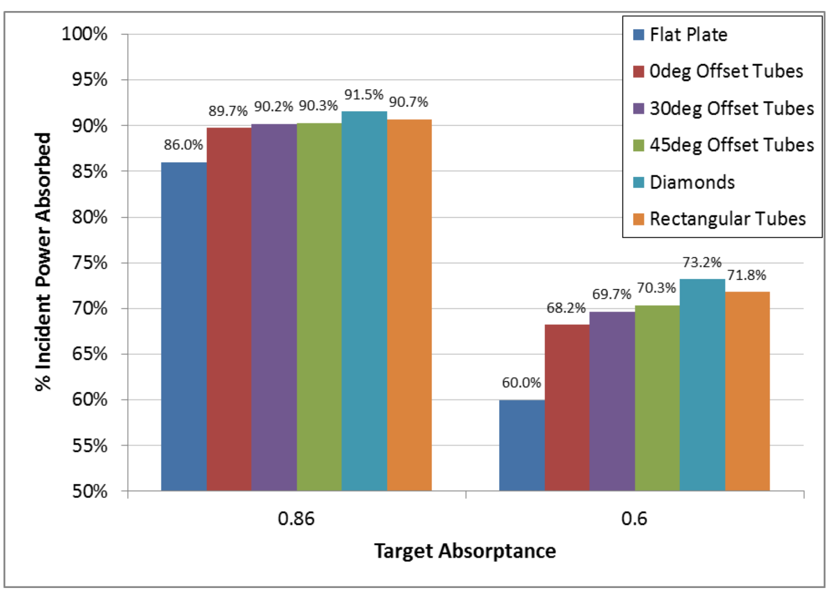


FIGURE 9. Results of the optical simulations showing absorptance improvements from the fractal-like receiver geometries relative to a flat plate receiver.

CONCLUSIONS

Fractal-like receiver designs with novel light-trapping geometries and features at multiple length scales have been developed and tested. At the macro scale, bladed panel configurations were simulated and shown to reduce radiative heat losses and increase thermal efficiencies by increasing the effective solar absorptance and reducing heat losses. At the meso scale, novel tubular geometries were modeled and tested to evaluate their impacts on the effective solar absorptance and thermal efficiency. Modeling results showed that the corrugated structures could increase the effective solar absorptance by several percentage points at intrinsic material solar absorptances of ~85%, and the impact was greater when the intrinsic material solar absorptance was lower. At high material intrinsic solar absorptances (95% or greater), the enhancement was negligible. The thermal efficiency could also be increased by several percentage points depending on the intrinsic solar absorptance. Preliminary structural analyses showed that high stresses near corners could exceed the maximum allowable stress for certain working fluids and operational conditions. Rounded corners and thicker tubes could alleviate the problem.

Tests were performed using meso-scale prototypes fabricated from Inconel 718 using powder-bed fusion additive manufacturing techniques. The parts were exposed to 30 W/cm^2 in a solar furnace and reached temperatures of ~700 °C. Measurements of the irradiance distribution and comparisons with ray-tracing models showed that the effective solar absorptance was increased in parts with corrugations and fins and corroborated the modeling results.

Current results indicate that the use of fractal-like geometries and features at both the meso and macro scales can increase the effective solar absorptance of oxidized substrates (e.g., Haynes 230, Inconel 718) from ~90% to greater than 95% without the need for coatings or high-temperature paints, which can degrade over time.

Future work will focus on calorimetric tests to evaluate the thermal efficiency of these fractal-like geometries at both the meso and macro scales..

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