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Development of Rotary Solar Receiver and Solar Simulator Facility for Concentrated Solar Power Applications

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Abstract. A prototype rotary solar receiver and a solar simulator facility have been designed, built and commissioned by Odqa Renewable Energy Technologies in conjunction with The Oxford Thermofluids Institute, University of Oxford for the validation of concentrated solar power technologies. The key features of the rotary solar thermal receiver include the rotating absorber surface which incorporates a high temperature heat transfer design. The innovative design also includes a compact solar power inlet aperture for very high incident heat flux to reduce the radiant heat loss from the high temperature surface. Air is used as the heat transfer fluid as this has system integration advantages over other types of heat transfer media, such as CO2, steam, molten salt, or solid particles. A 30kWe Xenon-arc lamp high heat flux incident light has also been developed to enable experimental validation of the solar receiver technologies. The Xenon-arc lamp array consists of three lamps combined with a custom designed, 5-degree-of-freedom focusing mechanism to achieve precise focus and maximise the heat flux. The receiver has successfully produced working fluid temperatures reaching 1200 °C, demonstrating the concept viability for high temperature processes.

Keywords: Rotary Receiver, Solar Thermal Receiver, Solar Simulator, High Temperature Air, Concentrated Solar Power

1. Introduction

Solar thermal receiver technologies for central solar tower applications utilise solar radiation concentrated by optical elements, such as heliostats field or parabolic reflectors, to produce high grade heat, which may be converted locally or transferred to energy storage systems. The ideal system efficiency for concentrated solar power plants is maximised with higher solar concentration [1], thus driving the need for high operating temperature.

Solar receivers in such plants experience extreme thermal conditions which are challenging to design for. A dominant thermal loss mechanism is radiative heat emission from hot surfaces of the solar receiver, which must be managed for high thermal efficiency. Operation at high temperature also leads to mechanical issues ranging from thermal stresses in components to degradation of materials through oxidation, which can potentially threaten the integrity of flow paths for heat transfer fluids within the machine. The use of air as the heat transfer fluid in solar receivers offers chemical stability at higher temperatures (<1500 °C) and is abundantly available [2]. These factors lead to the choice of the heat transfer fluid and materials in the current design.

1.1 Contemporary Solar Receiver Technologies

Earlier solar thermal receiver testbeds using air as the heat transfer fluid such as open volumetric receivers HiTRec and Solair-200 [3,4] have stationary absorbers where the main heat absorber operates in a static frame of reference. The need for a mechanical interface with rotating components was avoided; this design produced an air temperature output of 840 °C.

The development of rotary-type receivers opens up the potential for higher transient operating temperatures. The CR5 thermochemical heat engine concept was developed as a rotary-type receiver for a two-step hydrogen-splitting thermochemical cycle [5] which requires temperatures between ~320 and ~2000 °C. The design features porous catalyst matrices installed on a set of counter-rotating rings where reactants pass through. Other rotary receivers use particles as the heat transfer fluid include [6]. More recent development in the rotary-type receiver using air as the heat transfer fluid includes [7], which features rotating discs which resemble a stack of annular fins capable of producing an output air temperature at ~675 °C. Odqa's solar receiver uses a novel rotating design to achieve very high gas temperatures and high efficiency under highly concentrated solar radiation (~2000 solar concentration).

2. Evolution of Odqa's Analysis and Test Facilities

The development of Odqa's rotary solar thermal receivers began in 2019, incorporating advanced thermal management strategies adopted from state-of-the-art gas turbine technologies to provide highly effective heat transfer at high temperature to produce high output air temperatures reaching 1200 °C.

Testing of the first generation receivers was initially carried out using sunlight in field tests in mid-2020. The development of solar receivers for high temperature operation must be supported by high power radiant heat source. In-house high power solar simulation capability facility has been designed and commissioned in 2022 to realise these extreme test conditions. A schematic diagram and a photograph of the current test facility is shown in figures 1 and 2. The result is the continual progression of the maximum temperature achieved by new generations of receiver designs (figure 7). Various safety features have been incorporated into the solar simulator, which include reflector cooling fans powered by an uninterruptable power supply to prevent the overheating reported by [8], and interlocks to protect both the reflector and the solar receiver.

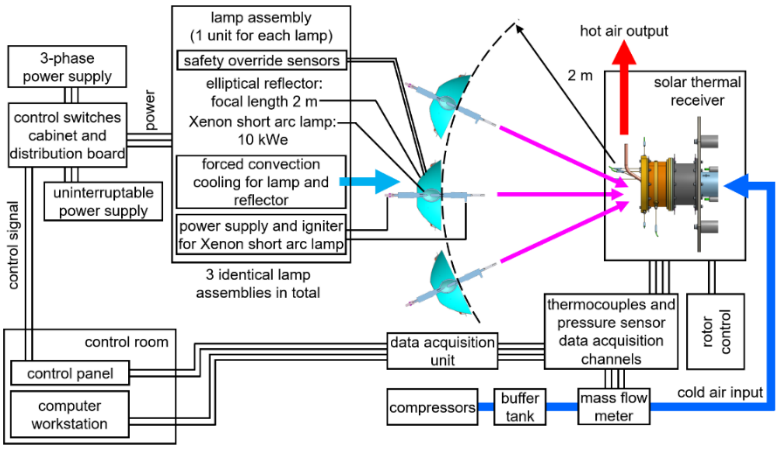

Figure 1. Schematic diagram of the current solar simulator and receiver test setup.

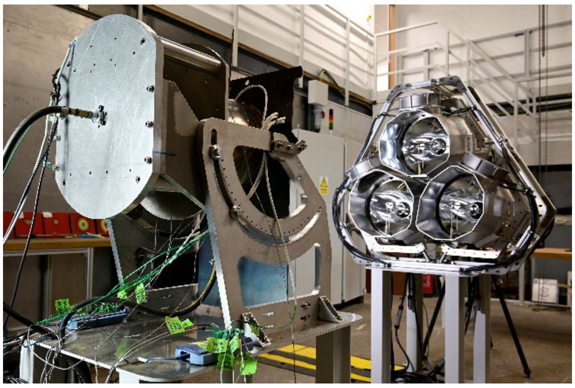

Figure 2. Photograph of the current solar simulator and receiver test setup.

2.1 Initial Field Testing and Simulation Capabilities

Initial field tests were carried out on the first generation rotary solar thermal receiver design which harvests solar power directly from the sun for high grade heat output using air as the heat transfer fluid (figure 3a, 3b, and 3c). The testbed was equipped with a Fresnel lens of size 1400 mm × 1050 mm and 1.2 m focal length. The solar heat rate captured by the Fresnel lens at a solar irradiance level of 880 W/m^2 is estimated to be 1.3 kW at maximum heat flux of 1.2 MW/m^2.

In parallel, in-house high fidelity solar heat flux analysis capability for complex 3-dimensional geometries has been developed using the photon distribution output from the Tonatiuh ray tracing software in the in-house heat flux analysis MATLAB code (figure 3d). The ability to quantify the solar heat flux distribution at sub-millimeter resolution has made significant contribution to the improvement in the aperture design.

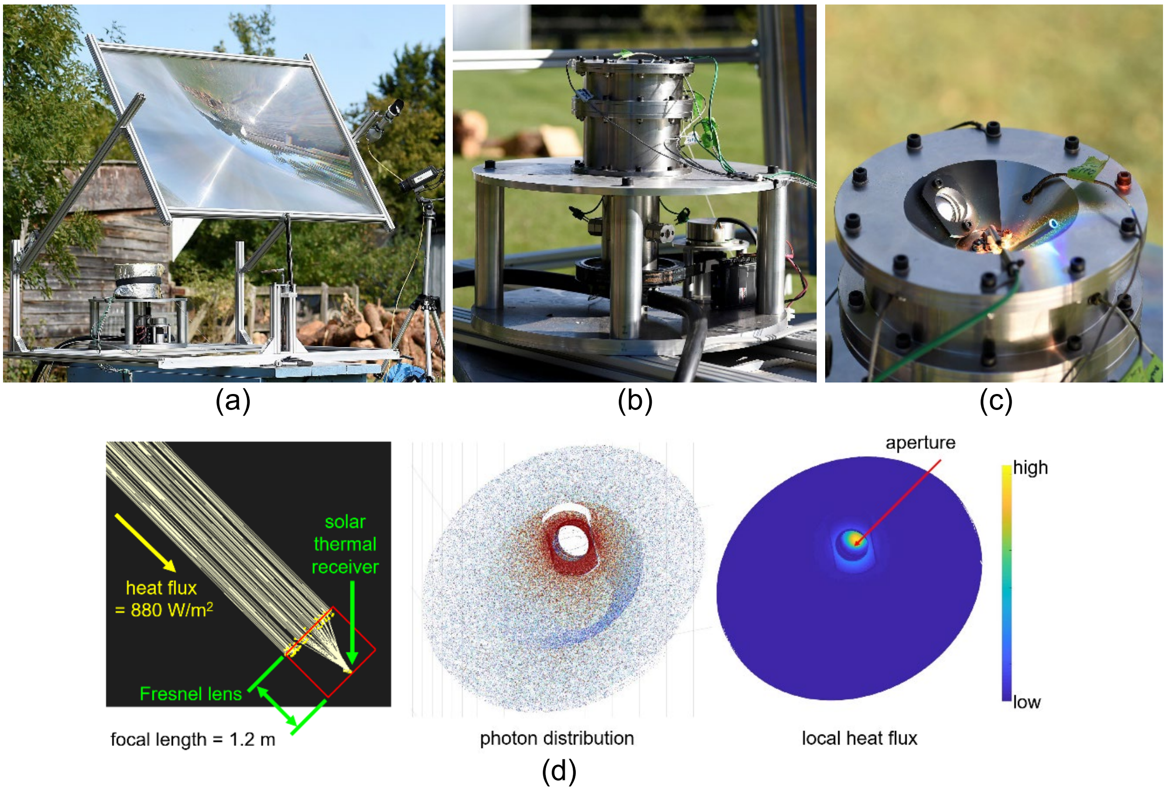

Figure 3. First generation solar receiver: photograph of (a) field test; (b) solar receiver assembly; (c) close-up of the machine; and (d) ray tracing simulation for full surface heat flux.

2.2 Bespoke Solar Simulator Development

A bespoke 30 kWe Xenon solar simulator has been designed and tested in Odqa's facility which consists of three Osram XBO 10 kWe Xenon short-arc lamps (figure 4a). The elliptical reflectors were custom designed to meet the focal length and the light cone angle requirements, which are 2 m from reflector rim to focus and a light cone angle of <15° respectively. A long focal length enables future expansion for addition solar simulator units; a narrow light cone angle allows a variety of CPC design strategies to be tested. The design of the optical elements for long focal length is particularly challenging: for a given lamp power the highest possible heat flux tends to reduce with the focal length; a larger reflector overall diameter would lead to increased reflected power of the focused beam however this would conflict with the narrow light cone angle requirement. Each lamp can be adjusted using the 5-degree of freedom focus mechanism (figure 4c) which allows the rotation of each lamp housing about two axes for pointing and also translation of the lamp along three axes, relative to the reflector. The resultant focused beam is shown in figure 4b.

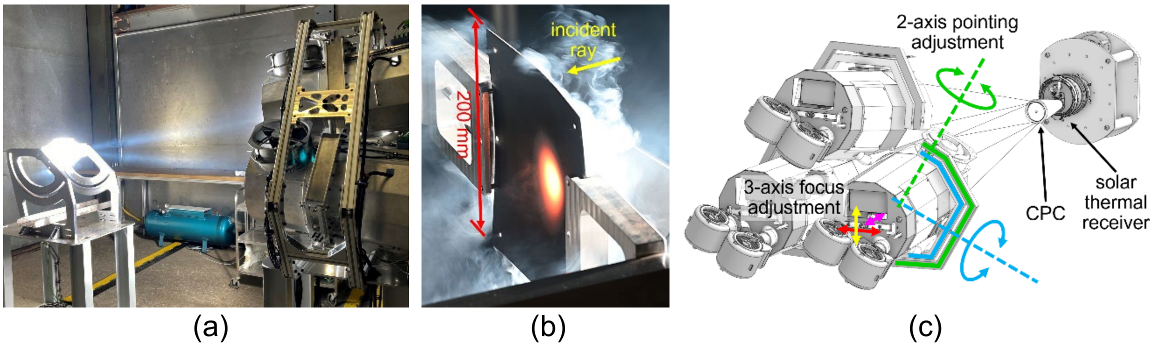

Figure 4. Odqa's 30 kWe Xenon solar simulator:
(a) solar simulator in operation; (b) focus test; and
(c) optical focus & alignment and future CPC test configuration

In-house optical analysis capability was deployed to verify the reflector design and to predict the peak heat flux level. For accurate representation of Xenon short-arc lamp in the simulation, the irradiance profile in the simulation is matched to data in the literature [9] as shown in figure 5a. There are two important features to match: 1) average angle, and 2) spread of the irradiance profile, where the former is considered more important.

The ray tracing results are shown in figure 4. In the current analysis the average angle of the Xenon lamp irradiance profile is well matched (figure 4a) data reported in [9], the irradiance profile is then applied to a range of bespoke reflector designs for peak heat flux comparison (figure 5b). The actual focal length has been successfully verified in the commissioning (figure 4b). The heat peak heat flux is predicted to be near 2 MW/m^2 (figure 5c and 5d) which is comparable to that of a heliostats field solar simulators such as [10].

The innovation in this optical configuration is enablement of tests for future revolved Compound Parabolic Concentrator (CPC) designs which in turn can potentially enable the light aperture size of the solar receiver to be minimised (figure 4c). A small light aperture size for solar receivers is necessary to reduce radiant heat loss and increase the potential for the design of thermally efficient machines.

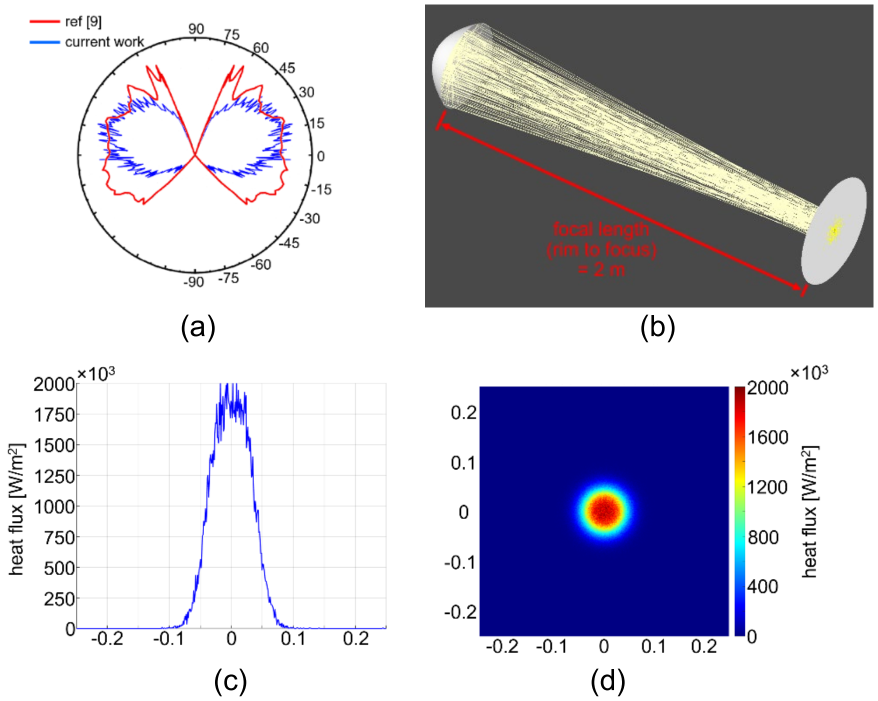

Figure 5. Xenon short arc lamp ray tracing in Tonatiuh:
(a) irradiance profile; (b) ray display for lamp installed with a single reflector;
(c) and (d) heat flux distribution at focal plane for 3-lamp array: cut-plane and 2D map.

3. Odqa Rotary Solar Thermal Receiver

Odqa's rotary solar receivers have undergone continual iteration for higher solar concentration. Significant progress has been made as a result of the continual development in the mechanical design and optical and aerothermal modelling. The improvements include: i) surface treatment for reduced oxidation on absorber for robustness; ii) carefully designed rotary seal to reduce the leakage of heat transfer fluid for higher efficiency; iii) heat transfer arrangement within the rotating absorber that has high temperature effectiveness (cf. heat exchanger effectiveness) and iv) reduced aperture size to minimise the radiant heat losses.

The latest design (figure 6) has been tested with the 30 kWe solar simulator (figure 5), the typical transient temperature for the same air mass flow rate is shown on figure 7. The fast initial temperature response for the heat transfer fluid indicates a high temperature effectiveness the heat transfer design has achieved. The overall temperature effectiveness of Odqa's rotary solar receiver is estimated to be as high as ~0.8 within the range of mass flow tested. The result of this high temperature effectiveness together with the high operating temperature led to the output air temperature reaching 1200 °C. Another contributing factor to the success of the current design in generating the air output temperature reported here is the meticulous mechanical design which ensures the integrity of the machine at component temperatures as high as 1300 °C. The mechanical design also minimises leakages within the machine. The machine can also be configured to utilise the peripheral incident radiant heat input around the aperture for the pre-heating of the heat transfer fluid to enhance the overall efficiency.

The progress made over the course of the development is show in figure 8. The first generation machine achieved 350 °C in the initial field tests took place in mid-2020. A 6.5 kWe commercial solar simulator unit was deployed to increase the irradiance input for the testing of the same machine, resulting in a marked temperature output improvement. Towards the end of the development for the first generation machine, air temperature output of 800 °C was achieved.

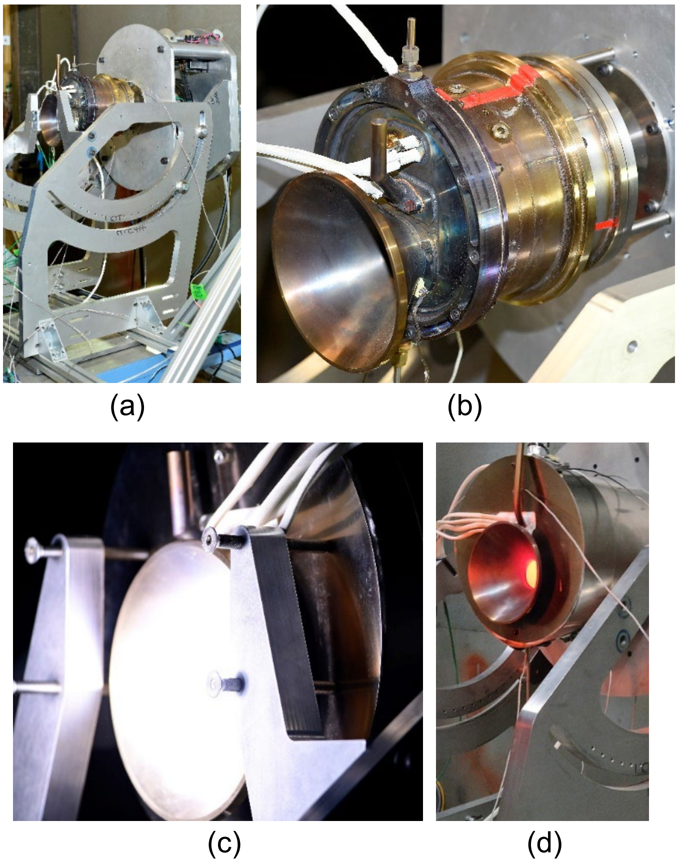

Figure 6. Prototype solar receiver: (a) assembly; (b) close-up of machine; (c) during operation; (d) rotary absorber surface glowing at high temperature immediately after test.

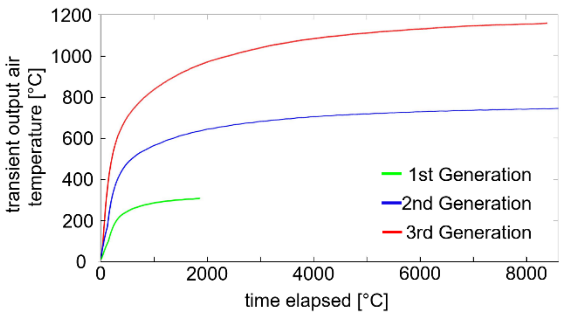

Figure 7. Odqa prototype test data: typical transient temperature.

The 6.5 kWe solar simulator was used throughout the test campaign of the second generation machine in 2021. The focus for the second generation was on the development of mechanical design to minimise leakages. As higher temperature is achieved the radiative heat loss becomes more dominant. In parallel, a heat transfer analytical model was developed to provide a much better understanding of the heat transfer mechanisms within the machine. The maximum temperature achieved during this period has reached 1000 °C. At the beginning of the development of the third generation machine, Odqa's bespoke Xenon short-arc 3-lamp array was commissioned in 2022. The design strategies developed as a result of the heat transfer analytical model were implemented. The maximum air outlet temperature achieved by the current generation machine is 1202 °C. The machine remained intact after the high power tests – its robustness has been demonstrated.

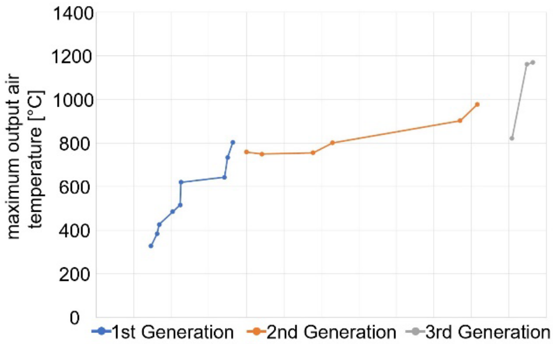

Figure 8. Main Outlet Gas Temperature Evolution

4. Summary and Conclusions

In this paper the testing facilities of Odqa for their solar receiver have been detailed and their capability shown, supported by the high fidelity ray tracing design methodologies. The Odqa solar receiver concept has been introduced with experimental data presented to illustrate the viability and potential of it as a product. To support the development of the solar thermal receiver a high power 30 kWe solar receiver has been designed and commissioned. A range of analytical capabilities in ray tracing and thermal analysis have been developed and deployed for the design of receiver and experimental facility. It can be concluded that the Odqa receiver is able to operate under extreme temperatures to produce an air output temperature of 1202°C.

5. Future Work

The following tasks will be undertaken in the coming months in order to enhance the output from the Odqa rotating solar receiver: i) inclusion of CPC into solar receiver to increase the solar concentration at receiver aperture; ii) continual enhancement of existing solar receiver, focused on the optimisation of heat transfer design and high temperature rotary sealing technologies for high efficiency and temperature effectiveness, and subsequently to further increase the air outlet temperature, and iii) design and deployment of next-generation receiver into a real solar tower facility for enhanced TRL demonstration.

Author contributions

Pok-Wang Kwan: writing, formal analysis, software, methodology; Robert Pearce: writing, formal analysis; Peter Ireland: conceptualisation, formal analysis, funding acquisition, methodology, supervision; Chiang Churchill Ngai: investigation, data curation, visualisation; Orla Mallon: resources; Ed Wood: conceptualisation, methodology, investigation, resources, visualisation, supervision, data curation; Mark Loasby: conceptualisation, methodology, investigation, resources, visualisation, supervision; Gediz Karaca: conceptualisation, funding acquisition, supervision.

Data availability statement

Data not available due to commercial restrictions.

Competing interests

The authors declare no competing interests.

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