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Upscaling and Testing of Air-Based Rotary Solar Thermal Receivers for Concentrated Solar Power Applications

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Abstract. Odqa Renewable Energy Technologies Ltd has successfully scaled its air-based rotary solar thermal receiver design from 10kW to 100kW. A 10kW-scale air-based rotary solar thermal receiver was tested in Odqa's in-house solar simulator facility in late-2022. Learning from the experience, an improved solar thermal receiver rotor geometry has been developed and built, its mechanical design has been proven in a heliostat field test carried out at PROTEAS, The Cyprus Institute. A Predictive Engineering Analytics approach has been developed to predict the thermal performance and for the purpose of upscaling of the solar thermal receiver. As a result, the thermal design for a 100kW-scale solar thermal receiver has been produced, which subsequently was built at Odqa and tested at the SynLight solar simulator facility at the Institute of Solar Research, German Aerospace Center (DLR).

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

1. Introduction

Odqa Renewable Energy Technologies Ltd, an engineering spin-out from Oxford Thermofluids Institute of the University of Oxford, started the development of its first prototype in 2019 designed for central tower mounted concentrated solar thermal receiver and the rate of development has been substantial. A range of solar thermal receivers have been tested in the fields with a Fresnel lens solar heat source as well as an in-house Xenon short-arc solar simulator [1], the capacity of which has been doubled to a total of 60kWe in the last quarter of 2023.

Odqa is focused on achieving scalability within a short timeframe. The development of prototype solar reactors producing a specific range of fuels could take over a decade. Odqa's approach differs: the exclusion of thermochemical processes from the solar thermal receiver design reduces the risks and complexity during the development stage. Direct supply of heat in a working fluid is a versatile commodity that can be adapted for a wide range of industrial processes including industrial drying, high temperature catalyst regeneration, or existing solar fuel production processes including Solid Oxide Electrolysis.

The choice of air as the working fluid for solar thermal receiver aligns with this design philosophy. Air is available in abundance and is non-corrosive in comparison with other working fluids such as molten salt, thus maximizing the use of common engineering materials that can be manipulated using conventional manufacturing routes so that the machine could potentially be produced at a minimal cost and large volume.

The working principle is simple: concentrated solar irradiance is received at the external surfaces of tubular absorbers and the heat is transferred to the working fluid. The fact that Odqa's solar receiver does not rely on chemical processes or phase change offers the potential for robustness, as well as reduced capital and operating expenditures.

2. Odqa's Innovation

The innovation in Odqa's Solar Thermal Receiver is the pressurized rotary tubular heat absorber that has been designed to operate at high solar concentration. The main rotary heat absorber section is encased in the insulation casing which has an aperture in the front. An additional peripheral heat absorber around the aperture has been introduced to enhance the overall power output of Solar thermal Receiver, which can be operated to provide additional preheating to the working fluid before the heating occurs in the main rotary heat absorber section.

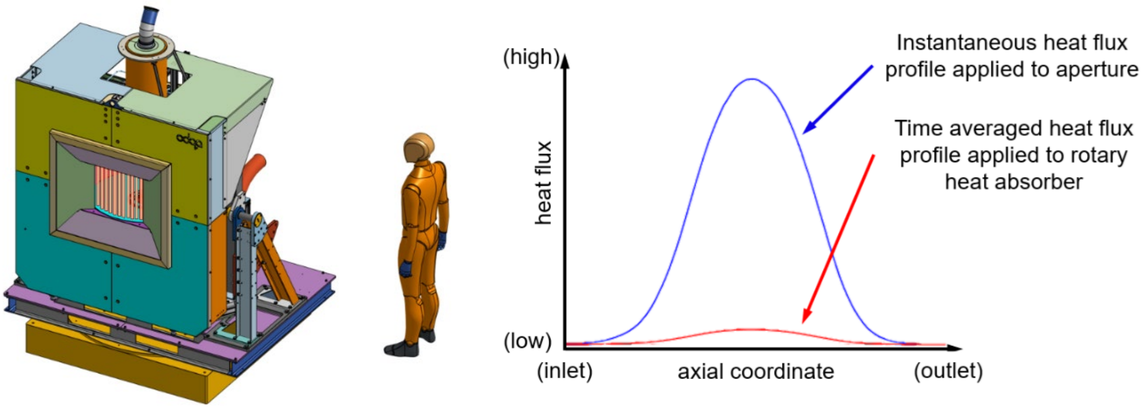

Figure 1. *Left: Odqa Air-based Rotary Solar design; right: Incident heat flux against effective apparent heat flux due to heat absorber rotation*

The incentives to design for a relatively higher output gas temperature are obvious, for example: the optimal overall efficiency of an ideal Carnot cycle with solar thermal receiver input requires an elevated solar concentration (>700 suns, where 1 sun = 1kW/m^2) and a matching target gas output temperature (>800°C). A higher gas temperature output can also drive a wider range of industrial processes, made possible by using air as the working fluid instead of molten salt.

Odqa has chosen the pressurized heat absorber configuration over the open volumetric configuration. The main benefit is the ability to operate the solar thermal receiver in a closed system where the most residual heat from the industrial process remains in the system instead of being rejected into the atmosphere. Another advantage of pressurization that it provides an option to use the pressure to drive heat absorber internal convective heat transfer to working fluid, which in turn increases the compactness of the machine.

The main advantage of the current solar receiver design is attributed to the use of a rotating absorber, which resolves two conflicting requirements simultaneously: 1) High solar concentration which leads to a small aperture design. 2) Inherently low thermal conductivity of air which leads to a large heat transfer area design (as implied by [2] and [3]). The emphasis in the thermal design has been placed on maximizing the machine output while keeping the hardware below the temperature limits of the chosen materials and the use of exotic materials has been avoided. An important aspect of the mechanical design is the development of high temperature rotary seals, which maintains the pressurization of the heat transfer fluid circuit. A significant amount of design effort in the hardware has been focused on the durability for long term operations and as well as the scalability of the manufacturing method which are based on the techniques that are commonly accessible: machining, sheet metal fabrication, and welding. Future commercial scaled solar receiver shall be based on similar production route which leads to a competitive manufacture cost.

A CAD image of a 100 kW-scale prototype solar receiver design is shown in figure 1. The external heat transfer areas of a portion of the absorber are exposed to high heat flux, but only for a fraction of a rotation cycle. The rotation reduces the time averaged heat flux applied to the absorbers to a level that matches with the internal convection heat transfer requirement. This is demonstrated in the graph shown in Figure 1, where the time averaged heat flux applied to the absorber of the receiver is considerably reduced in comparison to if it were stationary.

3. Aerothermal design

3.1 Predictive Engineering Analytics

For both the 10kW- and 100kW- scale prototype the main performance targets were: 1) Output gas temperature of 800°C; and 2) Output power of 10kW for the 10kW-scale machine and 100kW for the 100kW machine. The solar receiver is designed to operate at near atmospheric pressure. This decision benefits the hot gas circuit enabling it to operate at low gauge pressure so that the cost and complexity of all balance of plant is lower than for a system operating at significant pressure.

In the effort to develop Odqa's solar thermal receiver design for commercial production, a predictive engineering analytics approach has been developed. This approach informs the decision on: 1) Sizing of the major components. 2) Incident heat flux distribution to be applied at the aperture that would protect the heat absorbers from overheating while maximizing the output gas temperature and power. 3) Overall aerothermal performance of the Solar Thermal Receiver. In addition, this design tool allows Odqa to predict and compare quantitatively the benefits of a range of performance enhancement designs which are currently under development.

The backbone of it is formulated as a set of simultaneous equations, each describing the working principle and the interrelationship between components. Three main heat transfer mechanisms which govern the operation of the thermal design have been considered: 1) Convective and radiation losses from rotor. 2) Convective heat transfer within the heat absorber. And 3) Effect of conduction within the absorber. The model constants have been calibrated initially against using CFD and Tonatiuh ray tracing data.

3.2 Characterization of thermal performance

A typical plot generated using the design tool in figure 2. For brevity, the solar thermal receiver may be considered to have two inputs: 1) air mass flow ($\dot{m}_a$) at a given inlet condition specified by inlet air temperature (T_{ai}) and pressure (P_{ai}) (the inlet temperature-pressure pair set $\{T_{ai},P_{ai}\}$). 2) gross incident solar heat rate (Q_i) and heat flux distribution through the aperture of the machine.

The operation of the machine is constrained by: 1) the material temperature limit (*MT*). 2) pressure loss (*PL*) in the gas path. An acceptable design should be able to achieve the minimum: 1) output air temperature (*GT*). 2) power absorbed in the air (*QO*). For a given inlet condition $\{T_{ai},P_{ai}\}$, a feasible operating point on the performance curve represents the input mass rate $\dot{m}_a$ at a given gross heat rate input Q_i that can achieve the output temperature and heat rate requirements $\{GT,QO\}$ while the machine is kept below the heat absorber temperature and pressure loss limits simultaneously.

Each performance curve shows the extent of the operating region corresponding to thermal output exceeding the output performance target (i.e. the "feasible operating region") where the operating region covers the range of $\dot{m}_a$ that can achieve the target gas output temperature *GT* and gas output power *QO* within the material temperature *MT* and pressure loss *PL* limits (indicated by the shaded area in figure 2). The extent of the feasible operating region serves as a figure of merit for a thermal design. On this basis, a range of thermal designs for the 100kW-scale prototype were evaluated using this tool.

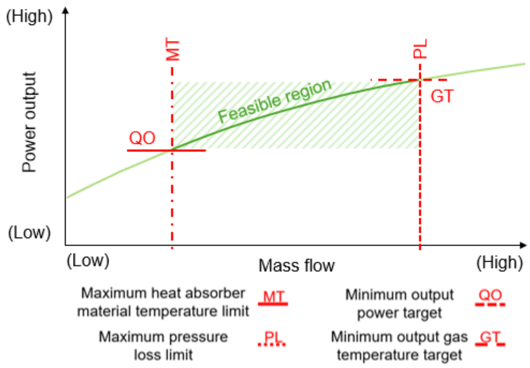

***Figure 2**. Operating region satisfying the system specifications.*

3.3 Calibration of thermal model

The model constants within the thermal model used in Predictive Engineering Analytic approach were calibrated iteratively as data were collected from the test campaigns at The Cyprus Institute's PROTEAS heliostats field [4] and DLR's the SynLight solar simulator [5] facilities; which will be discussed further in the section 5. Towards the end of the 100kW-scale test campaign, the predictive engineering analytics approach was used to predict the performance of the machine before the test took place. The procedure as follows: 1) Set input gas mass flow rate and aperture input power. 2) Use the predictive engineering analytics approach to predict the outcome: main rotary heat absorber peak temperature, output gas temperature, and output gas power. 3) Operate the machine in the test at the inputs as set in the prediction. And 4) Collect data for relevant output parameters. The performance of the 100kW-scale prototype has been predicted on this basis. The predicted output gas temperature and power are accurate to 3% and 6% respectively.

4. Testing of prototype Solar Thermal Receivers

4.1 In-house structural integrity test

The 10kW-scale prototype was designed primarily as a manufacturability trial (figure 3). The test campaign began in January 2023 with a preliminary in-house solar simulator thermal shock integrity test where the prototype was exposed to a step radiant heat input while operated at a flow rate below the design point. This test was designed to induce a rapid temperature change to the heat absorber main section where the thermal expansion of the was measured; dead-end pressure tests were carried out before and after testing to record sealing performance.

Figure 3. *Left: Odqa 10kW-scale solar thermal receiver in-house solar simulator tests; right: heliostat field.*

Figure 4. *Odqa 10kW-scale solar thermal receiver installed on PROTEAS solar tower.*

4.2 10kW-scale prototype Solar Thermal Receiver

The heliostat field testing of the 10kW-scale prototype was carried out between June and July 2023 at the PROTEAS heliostat field, The Cyprus Institute; note that the solar thermal receiver was not designed to match the solar output of the heliostats field and that the heliostat field was oversized relative to the solar thermal receiver. During the test campaign, 8 operational tests were performed where the range of mass flow tested was 2 – 6 g/s through the main heat absorber rotor (figures 3 and 4).

During the thermal performance characterization phase of the test, solar thermal receiver was subjected to a modest solar input. A gas output temperature of 780°C was achieved initially with a leakage as low as 4%. The deformation of the mechanical package was measured, data such as rotor thermal expansion various gap sizes were recorded at a rotor temperature of ~860°C. The maximum gas power output was ~14kW. In the maximum temperature test a gas output temperature of 1040°C was achieved.

4.3 100kW-scale prototype Solar Thermal Receiver

Following the success of the 10kW-scale Solar Thermal Receiver tests, the design campaign for the 100kW-scale prototype started in August 2023. A range of thermal designs were considered, with the final design selected from 20 configurations. Thermal design was produced using the Predictive Engineering Analytic approach discussed in section 4. The hardware can be operated in parallel-flow mode where air is pumped through the main rotary heat absorber and the peripheral heat absorber using different air moving devices or sharing the same inlet flowrate in series-flow mode where air is fed firstly into the peripheral heat absorber, the output of which is subsequently fed into the main rotary heat absorber at elevated temperatures. A variable tilting mechanism has also been developed to accommodate a range incident beam angle. Photographs are shown in figures 5 and 6.

Based on the same mechanical design and manufacturing approach, the 100kW-scale prototype was produced in March 2024 and tested at DLR's SynLight solar simulator facility between April and May 2024. Focus was placed in test campaign on understanding of the following aspects of the prototype: 1) Aerothermal performance characterization, 2) operation and durability of the mechanical design, 3) Provision of calibration data to validate the Predictive Engineering Analytic approach. The following were achieved:

- 15 full days of testing at 24 steady state operating conditions.
- 4 tests in parallel-flow mode, 11 tests in series-flow mode, and 4 tests in the tilted-axis configuration in series-flow mode.
- Main rotary absorber power output of 101 kW at output temperature of 806°C, 124.8 g/s mass flow. Overall gas power output of 121 kW in series-flow mode.
- Exceeded 190000 revolutions of the ultra-high temperature rotary seal.
- Exceeded 58 hours of operation time.
- Successful data acquisition for: 1) Performance characterization, also calibration of Predictive Engineering Analytic approach, Aerothermal operating conditions including spatial distribution and temporal variations in pressure and temperature in both rotary and stationary components. 2) Mechanical operating conditions including local thermal expansion in the structure and rotating speed of the main rotary heat absorber.

The advantage of metal air-based rotary solar thermal receiver is that the start-up time can be short, the test data has shown that Odqa's solar thermal receiver can consistently reach >85% of its steady state temperature within 30 minutes with a step incident heat input.

Figure 5. *Odqa 100kW-scale solar thermal receiver mounted in front of the Synlight, DLR Jülich.*

Figure 6. *Odqa 100kW-scale solar thermal receiver tested in the tilted-axis configuration.*

The overall performance of Odqa's 100kW Solar Thermal receiver is compared with air-based of solar thermal receivers reported in the literature in Table 1:

Table 1. *Comparison of performance of air-based solar thermal receivers with literature*

Reference	Output power [kW]	Mass flow rate [g/s]	Output temperature [°C]	Pressurization at inlet
Kribus et. al [6]	55	35	1000	Yes, >16 bara
Hoffschmidt et. al [7]	200	-	840	No
Heller et. al [8]	115	1200	960	Yes, 6.5 bara
Amsbeck et. al [9]	125.4	526	803	Yes, 3.84 bara
Hischier et. al [10], [11]	-	0.8-2.09	553-1062	Yes, 5 bara
Quero et. al [12]	-	3500-5750	400-800	Yes, 4.6 – 9.8 bara
Nakakura et. al [13]	13.2	16.1	564	No
Pabst et. al [14]	430	756	700	No
Current work	100	120	800	Yes, <2 bara

The advantage of heat absorber rotation is evident in the comparison with stationary heat absorber designs tested in Table 1; Odqa's air-based rotary solar thermal receiver is capable of low-pressure operation in a closed-loop system, which makes it the one of the few designs that can be operated with air-based thermal energy storage in a low-pressure system, such as [15], which are not designed as pressure vessel to avoid the complexity in the structural design.

6. Summary of achievements

The manufacturing route of a solar thermal receiver has been trialled based on the smaller 10kW-scale design. The manufacturing route has been shown feasible for upscaling from 10kW to 100kW. An advanced Predictive Engineering Analytics for thermal design tool to select suitable thermal designs has been developed and validated in a rigorous manner. The design cycle was dramatically accelerated. The meticulously designed mechanical hardware delivered by Odqa's engineers enabled the thermal design to be realized and put to experimental test. The result is the successful upscaling of Odqa's Air-based Rotary Solar Thermal Receiver by a factor of 10 in output power relative to the previous generation.

7. Future work

Further upscaling of the same thermal design by an order of magnitude is planned for future development. Future work also includes a demonstration plant coupled to thermal energy storage units and downstream industrial applications using high temperature air.

Author contributions

Pok-Wang Kwan: writing, formal analysis, software, methodology, data curation; Mark Loasby: conceptualisation, methodology, investigation, resources, visualisation, supervision; Augustin Wambersie: conceptualisation, methodology, investigation; Chiang Churchill Ngai: investigation, data curation, visualisation; Peter Ireland: conceptualisation, funding acquisition, methodology, data curation, supervision; Orla Mallon: resources; Katarina Marčeta: investigation; Orla Mallon: investigation; Aslı Kaya: investigation; Dave Mountain: investigation; Scott Battams: investigation: investigation; Ashley Cooper: investigation; MyeongGeun Choi: investigation; George Wilson: conceptualisation; Kirk Ashley-Morgan: investigation; 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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