

Spillage Recovery Devices for High Temperature Air-Based Solar Thermal Receivers

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Abstract. This paper presents the development and implementation of a novel approach to spillage recovery devices (SRDs) for high-temperature air-based solar thermal receivers by Odqa Renewable Energy Technologies Ltd. As concentrated solar thermal systems push towards higher operating temperatures to improve efficiency, spillage becomes a significant technical challenge, increasing both in flux and overall fraction of the incident power. Odqa's air-based receiver design however, leverages heat recovery and regeneration, allowing spillage to be repurposed rather than wasted. This paper investigates the impact of SRDs on some key CST parameters such as aperture size. The first section explores the sensitivity of receiver performance to SRD integration, while the second details Odqa's approach to developing such a system for a 100kW receiver prototype. The optimized SRD design, tailored to distinct operational conditions, demonstrates the feasibility of such an approach and their potential use as mechanism to increase the overall performance of CST systems cost.

Keywords: Solar Thermal Receiver, Spillage, 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 concentrated solar receiver (CSR) prototype in 2019. Odqa's objective is to rapidly demonstrate the scalability of its high temperature air-based receiver concept. A consequence of this increase in operating temperature is a need for higher mean aperture flux in order to reach optimal efficiency and performance. In turn, relative apertures sizes must be reduced at the expense of reducing the intercept factor or increasing the spillage - the flux landing outside of the aperture. With spillage levels exceeding 500 and sometimes even 700 solar concentrations, there is an impetus to use this highly concentrated, but otherwise wasted energy, with high temperature spillage already recovery featuring prominently in the *Concentrating Solar Power Gen3 Demonstration Roadmap* [1].

Secondary optics have been investigated as a means to reflect this spillage into the aperture, however maintaining highly reflective specular surfaces under harsh conditions remains a challenge [2], with strict temperature limitations of such materials being hard to reliably maintain. The efficiency of diffuse reflectors is also too low to be practical.

One significant benefit of air-based solar thermal receivers are the extensive possibilities for heat recovery and regeneration - something challenging to implement for molten salt receivers which would require secondary water-based loops for lower temperature spillage recovery [3]. The unrestricted operating temperatures of the air allow it to be used for both low and high temperature receiver designs. In this vein, spillage recovery devices (SRD) surrounding the aperture, such as the one developed by Odqa Renewable Energy Technologies, can prove an efficient, cost-effective manner to make use of spillage and increase the overall system efficiency. Moreover, these features, deployed as preheaters to a primary high temperature receiver, can play a significant role in the heliostat requirements and overall system design. As spillage is partially recovered, the balance between spillage and aperture re-emission is shifted with consequences for aperture sizing and knock-on effects on heliostat optical requirements. Previous versions of SRDs, also known as spillage skirts, have been employed in cavity receivers, however these have only been used at lower temperatures, for receivers with operating temperatures below 600°C [4,5].

Technical challenges facing SRDs for high temperature Gen3 receivers are significant, given the very high flux values and gradients that exist around the aperture. However, by combining appropriate surface emissivity as well as enhanced, optimized heat transfer mechanisms Odqa has demonstrated a workable solution, supporting its progress towards high temperature solar thermal receivers.

This paper contains two sections, the first investigates the sensitivities of system performance to the installation of generic SRDs. This is carried out using Monte Carlo Ray Tracing (MCRT). The second examines the approach taken by Odqa to implement this solution around its next high temperature air-based solar thermal receiver at the 100kW receiver scale. These systems have already successfully been tested at the PROTEAS Cyprus Institute (PROTEAS) [6] and the Synlight solar simulator facility at the Institute of Solar Research, German Aerospace Center (DLR-Synlight) [7] during previous test campaigns at 10kw and 100kW scales respectively. The SRD is optimized for the distinct operating conditions, using a combination of MCRT, CFD and low order aerothermal models. Numerical models and experimental results from tests at DLR-Synlight successfully demonstrated the use of spillage recovery systems a means to meaningfully increase the overall system power and peak temperature, highlighting Odqa's ability to rapidly design, build and test novel high temperature air-based CSR concepts.

2. Sensitivity study on the benefits of spillage recovery devices

The addition of a SRD, effectively a secondary receiver around the primary receiver aperture, adds additional complexity and cost to the overall system. However, the benefits of such a system can easily be demonstrated. With intercept efficiencies typically varying between 75% and 90%, depending on aperture sizing, there is a significant fraction of incident power that remains unused. Furthermore, given the emphasis of Odqa's CSR technology on high temperature receivers, the intercept factor will be expected to lie on the low end of the range.

In the proposed implementation, the SRD and the primary receiver are connected in series such that the SRD acts as a preheater to the primary receiver. In Odqa's design, this primary receiver is configured much like a cavity receiver, with a single, directional aperture, approximated in this study as a flat plate. The SRD, acting as a lower temperature and lower concentration receiver, is theoretically able to achieve higher efficiencies due to lower temperatures relative to the primary receiver. In this arrangement, the spillage recovery device is required to match the mass flowrate of the primary receiver. In this study, the effect of preheating the heat transfer fluid on the primary receiver's efficiency and performance is not considered, however, the overall benefits are known to be significant. By reducing the total gas temperature lift required of the primary receiver, the device can be built more compactly and with lower material temperature gradients.

In order to demonstrate the sensitivity of CSR design to a SRD, a heliostat field model based on the solar field at the IMDEA Energy Institute [8] was generated in Tonatiuh++ [9] as shown in Fig 1a. This site also happens to be the planned location of tests for Odqa's the SHARP-sCO₂ [10] test campaign. In each case, a square flat plate target was used. The area of the aperture as well as the aimpoint offsets as defined by the aimpoint strategy detailed by [11] were left as variables. Flux landing within 0.5m of the aperture was also measured. The Tonatiuh++ model was then incorporated within a MATLAB [12] routine which was able to find the pareto front between the aperture size, gross aperture power and aimpoint strategy, reflected in the aperture peak flux. This data was further processed by estimating the net power absorbed by the receiver given an estimated aperture loss. This was calculated using a mean absorptivity/emissivity of 0.9 and a uniform surface temperature as defined by Equation (1)

$$N = G\varepsilon - A\sigma\varepsilon T^4 + (S \times E) \quad (1)$$

where N,G, ε , A, σ , T, S, E represent Net power into the receiver, Gross incident aperture power, emissivity/absorptivity, aperture area, Stephan-Boltzmann constant, temperature, spillage power and SRD overall efficiency respectively.

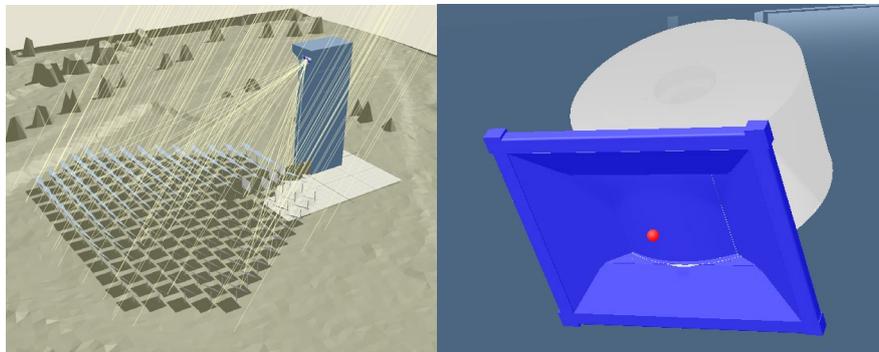


Figure 1. a) Left: Tonatiuh++ model of the IMDEA Energy institute Heliostat field, shown at noon Equinox. B) Right: close up of 3D geometry used for section analysis.

These 3D pareto fronts are plotted below, for different aperture temperatures and different SRD efficiencies. Each plot indicates an optimum aperture area for a given peak flux, with the peak flux being a function of heliostat aiming strategy. In practice, the peak flux is limited by the material and thermal characteristics of the primary receiver.

Net receiver power (w/m2)

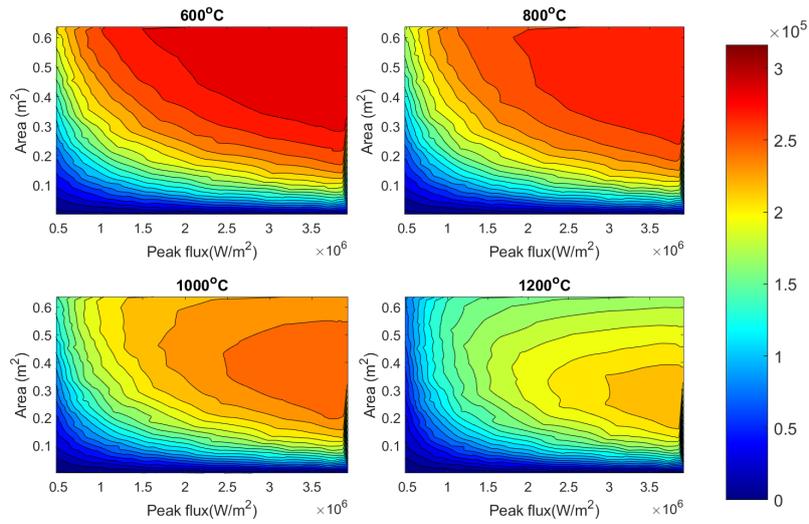


Figure 2. Pareto front for baseline case with no SRD at different mean aperture temperatures, showing tradeoff between aperture size, peak aperture flux and net receiver power as defined in Eq (1).

As expected, for a given heliostat field, as the mean aperture temperature increases, the optimal aperture area is reduced, and a higher peak flux is required to meet a certain net power. This can be repeated for receivers with SRDs using Equation (1), resulting in a shift in optimal aperture area, as indicated by Figure 3, as the spillage is partially recovered.

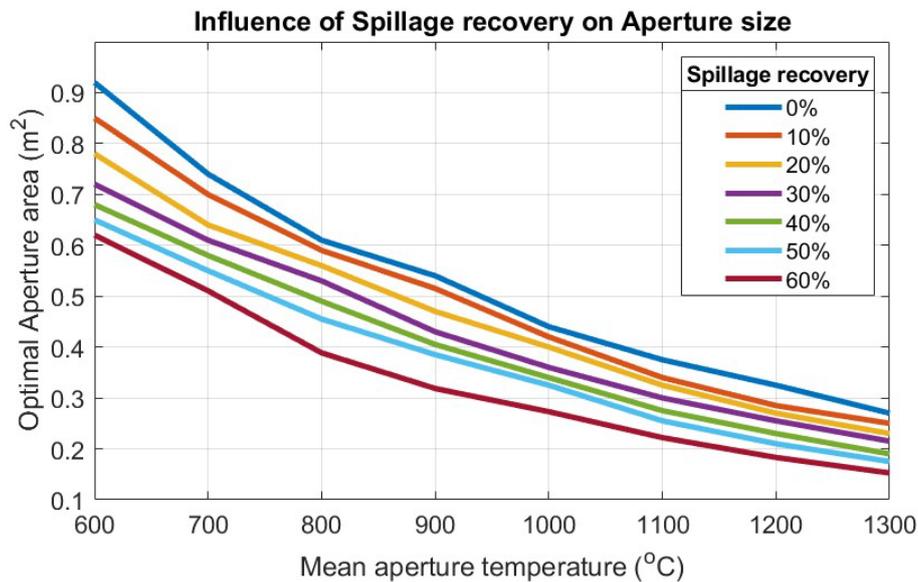


Figure 3. Optimal aperture area as a function of temperature for different SRD performances with peak fluxes of 3MW/m^2

The reduction in optimal aperture area, particularly at higher aperture temperatures is significant. As the lower concentration incident flux is absorbed in part by the SRD, the primary receiver can be downsized and optimised for only higher flux conditions.

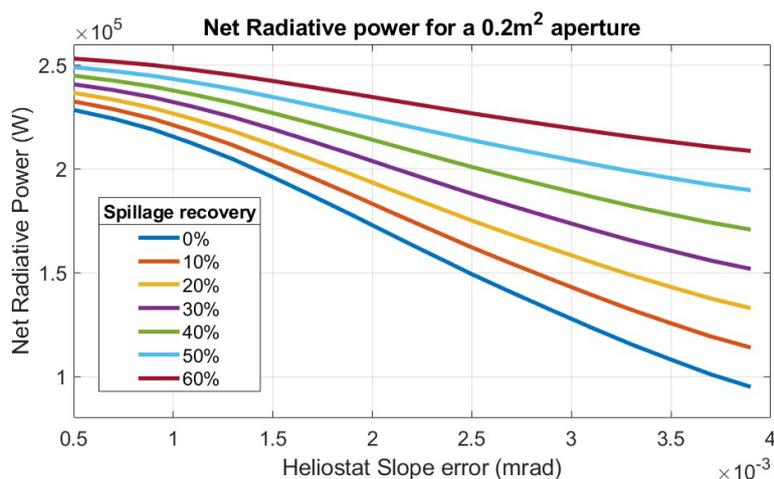


Figure 4. Plot of the influence of heliostat slope error against Net receiver power for different SRD performances.

Another potential impact of SRD's can be felt in the requirements of heliostat performance. The aiming performance and optical qualities of heliostats, combined to form the Heliostat Quality, is comprised of multiple parameters, one of which is the slope error as defined by [13]. The reduction of the heliostat error is known to lead to significant benefits to the overall plant performance. However, this performance comes at a cost. This is due to the fact that higher performing heliostats require stiffer structures, higher quality drives and more precise manufacture. With heliostats already comprising of upwards of 40% of CSP plant CAPEX, reducing heliostat requirements without compromising system performance may be preferable. Figure 4, demonstrates how a reduction in heliostat aiming requirements might be achieved due to an SRD. For example, in order to reach a net power of 200kW through a 0.2m² aperture, heliostat aiming requirements can be reduced from 1.4mrad to 2.1mrad by including a 30% effective SRD, resulting in a 6.6% reduction in facet costs as calculated by Yellowhair and Charles [14]. This cost reduction increases to 33% if an SRD of 50% effectiveness can be implemented, resulting in potentially significant reductions in heliostat field costs.



Figure 5. First iterations of Odqa's SRDs at 10kW and 100kW receiver scales respectively

3. Implementation of a high temperature spillage recovery device.

So far, the benefits of SRDs have been discussed with the assumption that a system of meaningful effectiveness can easily be developed at cost for high temperature receivers. This section details the approach taken by Odqa to develop such a system in the context of its next test campaign, comprising of a 100kW receiver to be tested using a heliostat field. This design approach has already been tested in parallel with Odqa's 10kW and 100kW receiver tests carried out at PROTEAS and DLR-Synlight respectively shown in Figure 5. In both cases, the SRDs were also designed to meet the specific flux distributions of both sites.

3.1 Design

The SRD was designed the several key objectives: a) to recover spillage and direct this heat to primary receiver, b) to minimise pressure losses across the system to avoid additional pumping power requirements, c) to fit in a compact package between the primary receiver and the exterior of the tower and d) to guarantee the protection of the primary receiver from high heat fluxes landing beyond the aperture. The SRD consists of 4 planar angled sub-units situated around the aperture and shown in Figure 1b. This illuminated plate receives a highly non-uniform flux distribution, which peaks towards the centre of the aperture. The backside of the illuminated plate is impingement cooled, with a variable impingement hole array cut out of an intermediate impingement plate. This impingement array is then fed by an additional plenum behind it. This arrangement, shown in more detail in Figure 6, allows for a highly compact design made entirely of laser cut sheet metal, with the impingement hole pattern defined to a high degree of accuracy.

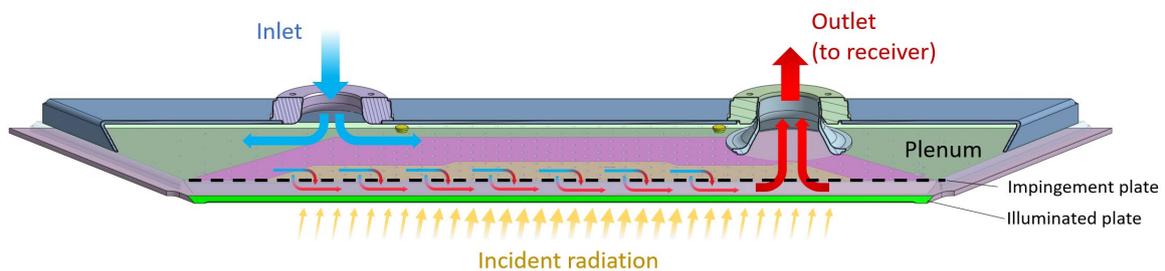


Figure 6. Mechanical design of one of the subunits comprising of Odqa's SRD

This hole distribution is and its resulting coolant flow is precisely modelled to ensure the SRD's performance. First, the incident flux distributions onto the 3D illuminated surfaces were modelled in Tonatiuh++ as shown in Figure 7. The distribution is then approximated to four 2D flux distributions, one for each main surface of the SRD. These were then set as heat flux boundary conditions within ANSYS Fluent [15], used to simulate the wall surface temperatures of the shadow plates. A fluid-shell model was used to simulate the fluid domain and a limited solid domain consisting only of the illuminated surface, allowing for conduction to be modelled across the target plate. The fluid flow was modelled across various mass flows and inlet pressures to simulate a range of conditions. Additionally, variable reflectivity, and flux conditions were used to represent the range of test conditions that might be tested.

This approach was used repeatedly across multiple hole pattern iterations in order to reach a cooling distribution that best matched the expected flux distribution, resulting in the highest output temperature of the system as well as the lowest minimum peak metal temperature. In order to size an initial guess, impingement cooling correlations by Florschuetz et al [16] were used to determine an approximately appropriate impingement cooling arrangement.

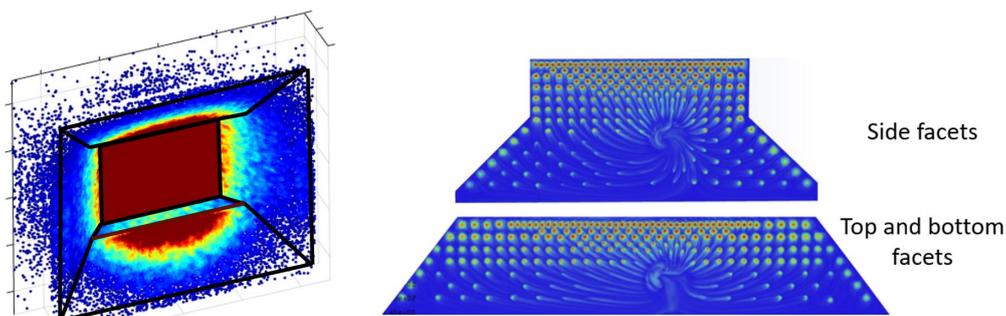


Figure 7. Left: Relative incident flux distribution on the SRD for a nominal operating condition. Right: Relative heat transfer coefficient distribution on the backside of the illuminated SRD plates.

3.2 Results

Numerical results indicated that at nominal operating conditions, the SRD can output a mean gas temperature of 303°C assuming an inlet temperature of 50°C, with an overall pressure drop of 20 mbar. The optimum design solution achieved the maximum gas temperature possible with acceptable SRD metal temperature and 20mbar pressure drop. The maximum metal temperature was selected to ensure adequate SRD life. This significant temperature lift and additional power is a substantial enhancer of the overall system.. Furthermore, a smaller temperature rise is required from the primary receiver, which can in turn be optimised for higher mean fluxes. Measured experimental results from a previous iteration of Odqa's SRD tested at DLR Synlight showed peak primary receiver inlet temperatures of >300°C, and an SRD thermal efficiency of 25-32%, taken as the ratio between gross incident radiation and net thermal power output. However, this includes the effect of a 0.26 nominal emissivity coating, kept in place to maintain the SRD output and metal temperatures low due to material limitations of intermediate piping in both the SRD and the remaining balance of plant. Tests showed that inclusion of the SRD to pre-heat air delivered to the existing receiver improved the output by 20%. Additionally, a primary function of the SRD remains to protect the primary receiver from potentially damaging spillage, meaning that a conservative design remains preferable.

4. Conclusion

A high temperature spillage recovery device has been designed and tested. Whilst still in its early stages of development, with low overall efficiencies relative current state of the art receivers, the system can provide significant enhancements to Odqa's novel receiver system. In addition, SRD can allow for other reductions in costs elsewhere in the system, in the form of reduced aperture dimensions and heliostat requirements. Further development will continue to be carried out in order to drive the effectiveness of spillage recovery devices whilst minimising additional cost and driving pressure requirements to the system. Finally, the rapid development of this system demonstrates Odqa's ability to transfer its aerothermal expertise into CST, using aerospace design tools and techniques to rapidly develop novel air based high temperature systems.

Data availability statement

Data not available due to commercial restrictions.

Competing interests

The authors declare that they have no competing interests.

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