Bladed Receivers with Active Airflow Control (BRAAC)

Project results and lessons learnt

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Contact name:	Dr John Pye
Title:	Senior Lecturer, Australian National University
Email: john.pye@anu.edu.au	**Phone:** +61 2 6125 8778
Website:	http://stg.anu.edu.au/

Project summary

In concentrating solar power (CSP), the receiver is the part of the system where concentrated sunlight is absorbed and converted to heat, which in turn heats up a working fluid that is being pumped through the receiver. This fluid conveys the thermal energy to the rest of the system, where it can be stored and eventually used to produce electricity or to provide heat to other kinds of industrial processes.

This project focussed on improving the performance of tubular molten salt receivers, which have been the preferred receivers for several large-scale systems such as the Gemasolar, Crescent Dunes and Noor III solar towers. The properties of the molten salt material are such that the temperature range is limited to 290–565°C, and the flux incident on the receiver tubes cannot exceed certain limits due to excessive thermal stresses in the tubes, and chemical degradation of the salt material.

In this project, a concept to overcome the flux limits in molten salt receivers was proposed. The concept was to rearrange the banks of tubes that make up the solar-thermal receiver into 'bladed' structure, similar to a louvred window. This configuration allows a much larger tube surface area to be squeezed into a specified receiver aperture area, hence allowing a much higher aperture flux for a given tube-surface flux limit. A bladed structure would be modular, in contrast with cavity receiver designs that are more commonly considered, and could be repeated many times across a large receiver without resulting in an excessively large size. The bladed structure would also have improved light-trapping properties, and decreased convective heat loss, due to the cavity-like structures that would impede the flow of air over the hottest parts of the structure.

An additional concept introduced in this project was the idea of adding 'active airflow control' to the design of a receiver. This means using air jets, or 'air curtains' similar to those used in the main doorways of department stores, as a way to reduce the loss of heat from the hot receiver surface by convection. Although it was found that this concept had been contemplated in the past, a patented new approach for active airflow was developed by the project, and evaluated in this project.

The overall aim of this project was to demonstrate that these novel concepts for receiver design could be developed and applied successfully to CSP to achieve improvements in system performance and facilitate a reduction in the resulting cost of electricity from CSP systems.

Project scope

The activities of the project, therefore, were designed to develop and examine this concept. The activities included lab-scale measurement of natural convection heat loss, wind-tunnel testing, computational models of the fluid flow over these structures, modelling of the optics of the bladed receiver shape, calculations of the thermal emission heat losses, and calculations of the internal heat transfer and pressure drops experienced by the working fluid (Figure 1). Models of each heat transfer process were developed and then these models were linked together to form a receiver design tool. Using the design tool, a best-possible flat receiver was designed, and then a bladed receiver design was found which could perform better than the best-possible flat receiver.

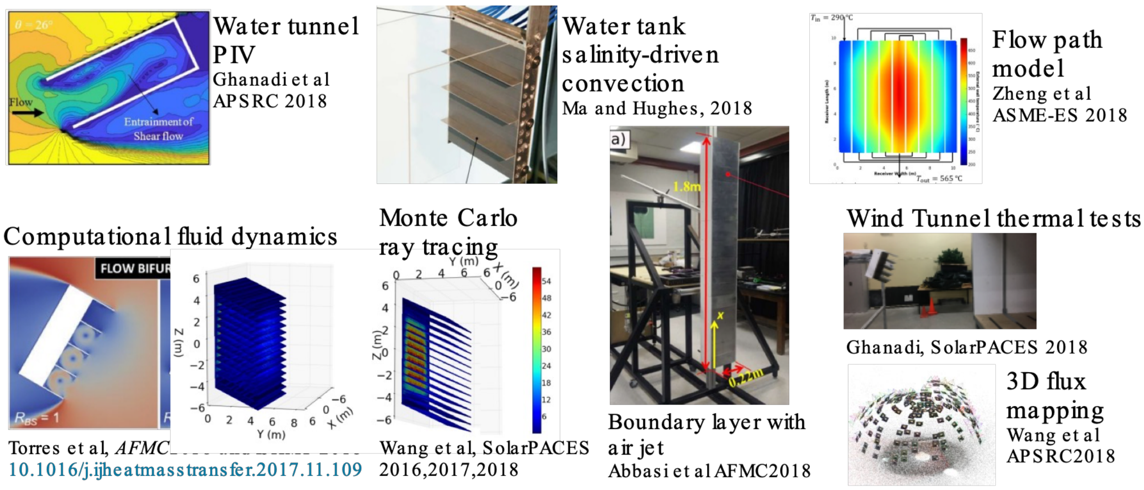

Figure 1. A wide range of computational and experimental activities were pursued in this project, in order to understand how to design bladed receivers and to maximise their performance.

Outcomes

Taking the PS10 central tower CSP system (near Seville, Spain) as the assumed system onto which a bladed receiver would be attached, it was found that a best-possible flat receiver on this system would achieve a 91.7% receiver efficiency, including spillage, reflection, convection and emission losses. After some iteration, a bladed receiver design was found with an estimated receiver efficiency of 94.1%. The modelling work confirmed that bladed designs could be used to increase the performance of tubular molten salt receivers.

A double-prototype was then built, incorporating the bladed receiver as well as the best-possible flat receiver, and subsequently tested at the CSIRO facility in Newcastle, NSW (Figure 2). The test results confirmed a performance gain for the bladed receiver, although with limited time for testing it was not possible to determine exactly how strong the gains were.

Some analysis of the cost-benefit trade-off for the bladed receiver was conducted. Although the bladed receiver design developed within the project was predicted to have a significant performance saving, it was estimated that the increased cost of the receiver would outweigh the benefits of the increased performance. A key reason for this was the fact that the overall receiver extent (aperture size) could not be greatly reduced because otherwise light from the furthest heliostats would be 'spilled', causing efficiency to be lost. Within the project, only a performance optimisation was conducted; there is likely to be some intermediate design where both cost savings and performance improvements can be identified, however it was not possible to pursue that topic within the limits of the project.

Beyond the specific work to develop and test the bladed receiver itself, there were a wide range of other outcomes from the project:

1. A novel method for measuring the performance of receivers was developed, based on taking many images of the receiver from various directions. This technique is likely to be applicable to many future receiver designs, and will facilitate an improved understanding of the breakdown of thermal and optical losses in different types of receivers.

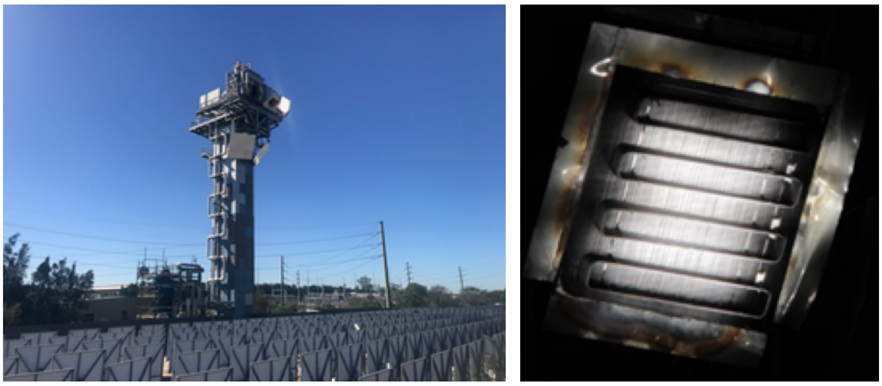

Figure 2: On-sun testing of the bladed receiver at CSIRO Newcastle.

2. Some pioneering fundamental work was done on the interaction of air curtains with natural convection boundary layers. To our knowledge, experiments of this kind have not been conducted before, and may yet lead to further new ideas for improved receiver designs.
3. Wind-tunnel and water-tunnel testing of heated flat and bladed structures was conducted, resulting in reusable data and observations applicable to future receiver design and model validation efforts.
4. Next, the accuracy with computational fluid dynamics simulations can be conducted for the purposes of receiver design was improved, and strong new capabilities were developed in this area.
5. A novel technique for on-sun testing using water and air was developed, as a result of the unavailability of molten salt at the CSIRO test facility.

By progressing through the process of testing two receivers at scale and on sun at the CSIRO facility, extensive experimental know-how was developed ranging from control systems to instrumentation, to testing protocols and techniques to maximise the precision of experiments that have been conducted. It is hoped that further activities in receiver design, such as those ongoing within the ASTRI program, can benefit from the many lessons learnt in this project.

Transferability

The capabilities in receiver design developed during this project are expected to have high value to ongoing efforts in other ARENA programs such as ASTRI, and the Australian involvement in the US Gen3 CSP program. Through this project, reusable tools for receiver design were developed, including for optical, external convection and internal flow modelling. Methods for calculation of external reflection and emission losses were developed. Open source software was released for the modelling of receiver optics (https://github.com/ANUstg/tracer).

Lessons learnt

Some key lessons learnt in this project are as follows:

- When developing novel pipework layouts and configurations, it is valuable to involve the people who will be involved in building the structure as early as possible, to identify areas for improvement the manufacturability of the design. Similarly, it is valuable to discuss testing plans with those responsible for the testing as early and possible.

- In testing high-temperature receivers, it is important to carefully consider not only the 'hot' parts of the system, but also the areas which will receiver 'spilled' flux, and ensure suitable shielding is used throughout. In the case of this project, additional shielding needed to be added to protect instrument cabling due to unexpectedly intense spilled flux.
- The receiver module built and tested in this project was extremely complex, resulting in a long design period, and consequent time pressure during the testing phase. Simplicity should be a priority for future designs, since this also implies savings in the final product.
- Thermocouple design, installation and layout are critical aspects of developing an experimental concept, and need specific focus. Differential thermocouples, and configurations able to minimise experimental uncertainty need careful thought.
- Whole-of-team design reviews were valuable in this project, but could have been held earlier in the project for greater benefit. These reviews highlighted important considerations and triggered further design iterations as a result of topics that had not been thoroughly considered earlier.
- Receiver design and concentrator (optical) design are closely coupled and should be developed in parallel. This project had as its scope only the receiver design, however in future activities (such as in ASTRI), attention should be paid to synchronising the design of both components, with the lowest-cost design strongly in mind.

Conclusion and next steps

A great deal was learnt during this project about the design and fabrication of solar thermal receivers. In this project, the design was very ambitious, and many difficult practical problems were tackled and overcome. The tools and understanding arising from this project are already being put to use in the ongoing ASTRI program to design a novel sodium receiver for next-generation CSP systems, and new PhD students are working on next-generation concepts for receivers and CSP systems.

The design of the receiver developed in this project was successful in meeting its objectives, but despite a high efficiency being achieved, the performance gains were ultimately not sufficient to outweigh the relatively high cost of the receiver, since it was found that optical constraints to the overall receiver size made it difficult to reduce the overall size of the receiver as much as had been anticipated. Consequently the receiver, being larger than anticipated, could not be as cheap as envisioned. This highlights the importance of early-stage of the costs and benefits likely from a new design concept. Such analysis was conducted in the proposal stage of this project, but key insights gained during the project rendered the initial estimates inaccurate.

Future efforts in receiver design will be more focussed on understanding material limits, since these were an assumed 'boundary condition' for this project – accepted without question. Instead, we need to understand material limits better, and how best to work right up to those limits. This is a key topic of investigation in the ASTRI program. Another key area is in higher-temperature designs. In this project, the operating temperature of the receiver was limited. Higher temperature receivers facilitate significant gains in other parts of a CSP system, and should be a major focus in future receiver design efforts, as it is in ASTRI and in other international programs.

Supporting information

The following publications are accessible for those wishing for extra information on the outcomes of this project. Please contact john.pye@anu.edu.au if you have any difficulty in obtaining any of these reports.

1. Y Wang, D Potter, C-A Asselineau, C Corsi, M Wagner, C Caliot, B Piaud, M Blanco, J-S Kim and J Pye, 2019. Verification of Optical Modelling of Sunshape and Surface Slope Errors for CSP Systems. Complete manuscript ready for submission to *Solar Energy.*

2. F Ghanadi, JF Torres, M Arjomandi and J Pye, 2019. Flow structure and mixed convection in a bladed solar receiver under wind conditions. Under review with *Experimental Thermal and Fluid Science*.

3. JF Torres, F Ghanadi, Y Wang, M Arjomandi and J Pye, 2019 Mixed convection and radiation from an isothermal bladed structure. Accepted subject to revisions by *International Journal of Heat and Mass Transfer*.

4. J Fang, N Tu, JF Torres, J Wei and J Pye, 2019. Numerical investigation of the natural convective heat loss of a solar central cavity receiver with air curtain. *Applied Thermal Engineering* **152***,* pp. 147-159. April. doi:10.1016/j.applthermaleng.2019.02.087

5. J Pye, M Zheng, Y Wang, F Venn, F Torres, L Ma, J-S Kim, G Hughes, F Ghanadi, J Coventry, M Arjomandi and E Abbasi, 2018 'Reconfiguring and rethinking tubular receivers: Findings from the Bladed Receivers with Active Airflow project', in *Asia-Pacific Solar Research Conference*, Sydney, Dec. (oral presentation)

6. Y Wang, W Lipiński and J Pye, 2018. 'Camera-based measurement of reflection and emission from complex receiver shapes', in *Asia-Pacific Solar Research Conference*, Sydney, Dec. (oral presentation)

7. JF Torres, F Ghanadi, I Nock, M Arjomandi and J Pye, 2018. 'Mixed convection from a tilted cuboid with an isothermal sidewall at moderate Reynolds numbers', *International Journal of Heat and Mass Transfer* **119**, pp. 418–432. doi:10.1016/j.ijheatmasstransfer.2017.11.109

8. F Ghanadi, M Arjomandi, JF Torres and JD Pye, 2018. Stability of a planar jet aerodynamic seal subjected to external cross-flow. 21st Australasian Fluid Mechanics Conference, Adelaide, 10-13 Dec. (oral presentation).

9. JF Torres, F Ghanadi, M Arjomandi and J Pye, 2018. Vortex dynamics within a bladed structure for mixed convection. *21st Australasian Fluid Mechanics Conference*, Adelaide, 10-13 Dec. (oral presentation+paper).

10. E Abbasi Shavazi, JF Torres, GO Hughes and JD Pye, 2018. Convection Heat Transfer from an Inclined Narrow Flat Plate with Uniform Flux Boundary Conditions. *21st Australasian Fluid Mechanics Conference*, Adelaide, 10-13 Dec. (oral presentation+paper).

11. J Pye, E Abbasi, M Arjomandi, J Coventry, F Ghanadi, G Hughes, J-S Kim, L Ma, A Shirazi, JF Torres, F Venn, Y Wang and M Zheng. Towards Testing of a Second-Generation Bladed Receiver, in *SolarPACES 2018,* Casablanca, Morocco, 2-5 Oct.

12. Y Wang, J Coventry and J Pye, 2018. Optical and Radiation Considerations in Bladed Receiver Designs for Central Tower Systems. *SolarPACES 2018*, Casablanca, Morocco, 2-5 Oct.
13. JF Torres, F Ghanadi, M Arjomandi and J Pye, 2018. Mixed Convective Heat Transfer from an Isothermal Bladed Structure. Mixed convective heat transfer from an isothermal bladed structure. Proceedings of the *11th Australasian Heat and Mass Transfer Conference*, Melbourne. 9-10 Jul. (oral presentation)
14. JF Torres, F Ghanadi, M Arjomandi and J Pye, 2017. 'Numerical investigation of mixed convection from a tilted flat solar thermal receiver' in *Asia Pacific Solar Research Conference*, Melbourne, Dec. (oral presentation)
15. F Ghanadi, JF Torres, M Arjomandi and J Pye, 2017. 'An experimental investigation of Reynolds number, wind direction and pitch angle effects on mixed convective heat losses from a flat plate receiver' in *Asia Pacific Solar Research Conference*, Melbourne, Dec. (oral presentation)
16. Y Wang, D Potter, CA Asselineau, M Wagner, L Li, C Corsi JS Kim and J Pye, 2017. 'Comparison of Optical Modeling Tools on Sun-shapes and Surface Slope Errors'. *SolarPACES 2017*, Chile, Oct (oral presentation)
17. JF Torres, Y Wang, M Zheng, J Coventry and J Pye, 2017. 'Coupled optical-hydrodynamic-CFD modelling of bladed receivers'. *SolarPACES 2017*, Chile, Oct (poster presentation).
18. Y Wang, C Asselineau, J Coventry and J Pye, 2016. 'Optical Performance of Bladed Receivers for CSP Systems' in *Proceedings of the ASME 2016 Power and Energy Conference,* Charlotte NC, 26–30 Jun.
19. Y Wang and J Pye, 2016. 'The Peak Flux Constraints on Bladed Receiver Performance in High-Temperature Molten Salt Concentrating Solar Power Systems' in *Asia Pacific Solar Research Conference,* Canberra, 30 Nov.
20. M Zheng and J Pye, 2016. 'Optimisation of Flat Tubular Molten Salt Receivers' in *Asia Pacific Solar Research Conference,* Canberra, 30 Nov.
21. I Nock, W Logie, J Coventry and J Pye, 2016. 'A Computational Evaluation of Convective Losses from Bladed Solar Thermal Receivers' in *Asia-Pacific Solar Research Conference,* Canberra, 30 Nov.
22. J Pye, J Coventry, C Ho, J Yellowhair, I Nock, Y Wang, E Abbasi, J Christian, J Ortega and G Hughes, 2016. 'Optical and Thermal Performance of Bladed Receivers' in *SolarPACES 2016,* Abu Dhabi, 13 Oct.