Improved high-temperature receivers for dish concentrators

Project results and lessons learnt

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Summary

In this project, a new receiver was designed, built and tested on the 500 m² 'SG4' Big Dish at ANU. This open cavity receiver has a capacity of 450 kWth, and converts focussed radiation into superheated steam with a theoretical efficiency of 98.7%. Very good agreement been experimental and theoretical efficiencies were found during the testing program in Nov-Dec 2015. Apart from testing result, the project has resulted in a reusable set of design tools that ANU will adopt on several other current projects. A potential commercial partner has been identified, and it is hoped that the new receiver will form part of commercial systems in the near future.

Project Overview

Project summary

Concentrating solar thermal power (CSP) technology makes use of concentrated solar radiation to provide heat for electricity generation and other applications such as industrial process heat and production of fuels. The focal point in a solar thermal concentrator is the receiver. This is where radiation from the sun is converted into usable heat. In most cases, a receiver is used to heat up a working fluid such as water or molten salt.

This project had as its aim the development of a highly-efficient receiver suitable for a dish concentrator. Dishes are considered to be the most efficient type of solar concentrator, and are able to achieve very high concentrated radiation intensity and very high temperatures as a result. At ANU, a large 500 m² dish called 'SG4' was completed in 2009. At that time, the optics of the receiver were carefully characterised. This dish, that largest solar dish in the world, was found to have exceptionally good optics, with a peak concentration ratio of 14,000 suns at its focus.

Receivers are complex things. They must be positioned to intercept and absorb as much as possible of the concentrated radiation and transfer it to a working fluid, while keeping various forms of heat loss minimised. The working fluid must not experience an excessively high pressure drop as it passes through the receiver, and the various parts of the receiver must not get too hot, both to avoid damage, but also to keep the heat losses minimised.

One of the difficulties identified at the outset was that very little work had been done on integrated tools to allow a receiver to be designed, bearing in mind all of these aspects of the receiver performance. Understanding each one of these loss mechanisms (spillage, reflection, convection, radiation, and conduction) requires detailed knowledge of a different physical process. Each loss mechanism is coupled to all of the others, since losses affect surface temperatures, and surface temperatures affect losses. There was a need to produce integrated models in order to be able to build a better receiver with higher performance. Better performance should mean that the cost of solar thermal energy can be lowered, which will increase the contribution that concentrated solar power can make to the renewable energy industry in Australia and globally, and hence to climate change mitigation.

The activities in this project were as follows: laboratory-scale experiments were developed to obtain qualitative and quantitative measures of natural convection heat loss from scaled-down model receivers; computer simulations of natural convection heat loss were built, and compared to the laboratory results; computer simulations were then used to guide a design/development process where a full-scale receiver design was formed and gradually optimised; the full-scale receiver was then built and tested, and its performance was compared with the predictions, including its impact on reducing the cost of electricity that could be generated.

All of these activities were completed, and the resulting receiver was found experimentally to achieve a 97% efficiency (allowing for all of the loss modes mentioned above). This result makes it possibly the most efficiency solar-thermal receiver to have been built and tested at full scale. Our simulations suggested an improvement from 94.6 % (for the earlier SG3 receiver) to 98.7% (for the new design) at reference conditions.

Project scope

Explain why you undertook the project.

The ANU SG4 dish was built in 2009, but there had never been a receiver specifically designed for it. It was hoped that by undertaking a careful study to fine-tune a receiver to the excellent optics of SG4, a high efficiency design could be demonstrated, and that it would help to advance the development and relevance of CSP dish technology.

What problem were you trying to solve?

We wanted to look at all of the aspects of receiver performance in an integrated way. At the time of starting the project, there were very few documented studies showing how all the trade-offs in receiver design could be correctly balanced. We wanted to understand the basic heat transfer processes, and then put them together and try to optimise for best efficiency. And we wanted to prove it, by building and testing the design.

What barrier were you trying to overcome?

At this point, the dominant CSP technologies are, firstly, parabolic troughs, which can't increase in efficiency very much further, because they aren't able to produce high-temperature working fluids. Secondly, central tower systems are limited by their receivers, which only achieve efficiencies of the order of 90%, because of peak flux limitations imposed by the molten salt working fluid and other materials constraints. We wanted to show that with a dish concentrator, we could greatly increase receiver efficiency, in the context of a CSP technology that has plenty of room for further efficiency improvement and cost reduction.

We also felt that receiver modelling capability was something that needed to be improved. We wanted to drive better innovation for CSP receivers by developing better tools that would allow more detailed understanding of how receivers perform, and how they can be improved.

What knowledge, skills, capability, technical, logistic or commercial advances were you trying to create?

In the ANU solar thermal group, we work on a range of CSP technologies. Through this project, we wanted to expand our skills and knowledge on design of receivers, not just for dish systems, but for other types of receivers as well.

We also wanted built a receiver that was matched to the SG4 dish. We felt that commercial adoption of the ANU dish technology would be greatly aided by an efficient and tested receiver.

Outcomes

Describe what actually happened.

Extensive experimental and computational results were reported in numerous conferences and journal publications. The culmination of the project was the testing of a full-scale receiver, approximately 1.5 m in diameter, at the focus of the 500 m^2 ANU 'SG4' Big Dish. A range of tests were performance in a one-month period at the end of the project, and achieved a 96.7% average efficiency across a range of conditions. For the same conditions, our models forecast an average of 98.7% efficiency – although these models don't include the effect of wind. We considered this to be proof that (a) we had built a very efficient receiver and (b) our models were in very good agreement with reality.

How did it advance technology or commercial readiness?

ANU is now in discussion with a company that is seeking to make use of the new receiver in a proposed commercial installation. A particular client in the mining industry is interested in the potential of our receiver in provision of solar steam for remote-area industrial processing. ANU hopes to obtain a license deal including some follow-on engineering activities to ensure that the receiver meets the company requirements.

How does what you achieved compare to what you hoped to achieve?

The performance of the new receiver exceeded our expectations.

Were there any surprising results?

Two big surprises in this project: firstly, when preparing to measure the optical performance of the Big Dish, we found that a significant number of the original mirror panels from the dish had become damaged in the weather, and had badly degraded the performance of the dish. We had to replace a large number of mirror panels with a more conservative design that would not suffer weather damage. Without replacing those mirror panels, we never would have been able to show this high level of performance.

Secondly, during testing of our receiver, there were some issues with the pump that was used to circulate water through the receiver. It was not able to produce the flow rates that were needed, and on one occasion, we actually melted a portion of the receiver. There was not time to replace the pump, so we proceeded with the pump we had. But we were very surprised that the receiver was able to melt, and we will be looking at that if the design work is taken any further.

Is there an interesting image/video/tool associated with your project you want people to know about?

We will be posting a full technical report from the project shortly, once a particular journal paper has undergone the review process.

Transferability

Explain how what you did/achieved can be applied to addressing problems/pursuing opportunities elsewhere. Please include your approach to sharing knowledge gained both within your organisation and more broadly.

We are using similar experimental and computational approaches to develop other solar thermal system components. In the project *Bladed Receivers with Active Airflow Control*, we are developing receivers for central tower systems that attempt to reproduce cavity-like benefits on low-cost central tower receivers. We're publishing our results regularly, and we are also contributing to several open-source software projects that other researchers and developers can use, including OpenFOAM (a CFD package for modelling the fluid flow around a receiver), Tracer (an optical simulation tool for predicting how light is absorbed on the receiver) and SolarTherm (an annual performance simulation tool, for forecasting how much electricity or other product a CSP system produces all year round). These tools and others are being used across several ANU projects, and members of the team from this project are transferring to other projects and transferring their knowledge with them as they go.

Can you provide a list of any other projects/tools in your area that contribute to the same field as you?

The community of researchers working on high-quality models of receivers, and on novel receiver designs, has grown in recent years. There are researchers in Germany, US, Spain, Israel, Mexico, UAE, France, Japan and other places who are working on this problem or at least aspects of it.

In this project one of our freely-shared outputs is development of the *Tracer* ray-tracing code, which can be used to simulate the optical performance of a CSP system together with its receiver. This tool is comparable with other tools such as SolTrace, Tonatiuh and DELSOL which are maintained by other researchers.

Conclusion and next steps

In this project, a new receiver design with a predicted 98.7% design-point efficiency was developed. This efficiency number includes the effects of spillage, receiver reflection, receiver thermal emissions, natural convection heat loss and conductive heat loss through insulation. This efficiency is exceptionally high, and we believe it may be the most efficient receiver yet to have been tested at full scale.

Our experimental results so far obtained an *average* performance of 96.7% efficiency across a range of conditions, and agree well with the modelled performance for those conditions.

Our project has increased Australian capacity in designing, constructing and testing world-class solar thermal concentrators. The SG4 dish is now a complete energy solution, and should be considered seriously for a range of energy applications both locally and overseas. Its particular niche initially may well be in remote-area thermal energy applications, such as in mining. It is very difficult for other renewable energy sources to provide high-temperature thermal energy as cost effectively as is possible with a system such as this one.

Lessons Learnt

Lessons Learnt Report
Improved high-temperature receivers for dish concentrators

Knowledge: Technical
Technology: Solar Thermal

1. **Integrated modelling of receiver losses.** We developed integrated CFD, ray-tracing, conductive and thermal emissions (radiosity) models as well as hydrodynamic flow model and wall heat transfer model, in order to obtain overall receiver performance. We developed approaches for iteratively converging the models when all of these mechanisms occur simultaneously.
2. **Importance of nonisothermal receivers.** We found that the variation in temperature on a receiver is something that must be actively used to enhance the receiver performance. Lower temperature regions should be placed where the receiver is more exposed to the environment, and higher temperature regions should be sheltered, preferably deep within a cavity, to reduce losses from those regions.
3. **Optimisation of receiver shapes.** We developed a novel approach to save on calculation time when assessing many (1000s) of receiver shapes. This approach saved us many millions of rays of computational cost.
4. **Performance of air curtains for receiver convective loss reduction.** We ran numerical and experimental tests and found that a well-placed air jet with an optimised velocity can reduce cavity convective heat loss by 40-70%. We aim to incorporate active airflow features in future receiver designs.