Computational and experimental investigations into cavity receiver heat loss for solar thermal concentrators

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Abstract

Tubular cavity receivers offer excellent prospects as low-cost, high-efficiency heat collection elements for paraboloidal dish solar-thermal concentrators, as well as for central tower systems. Major heat loss mechanisms for these receivers are convection and radiative emission, as well as reflection and spillage (non-capture). Compared to glazed receivers, convection heat loss can be quite a large fraction of the total, though the losses depend on solar elevation angle; at higher angles, and in low-wind conditions, a trapped buoyant region of air inside the receiver helps to suppress the convective losses. Radiative losses can be reduced through selective surface coatings, as well as through optimised cavity geometry, to reduce the view factor from the heated surface to the surroundings.

This paper is a progress report for an ANU-led project to increase receiver efficiency by at least 2%. Experimental studies using an electrically-heated air cavity are presented, which are making use of thermal imaging to improve accuracy compared to earlier studies; planned tests will extend this work to several non-cylindrical cavity geometries, to assess whether predicted efficiency improvement can be shown in practise. Air-curtain effects are also under investigation, including through an initial series of tests with an analogous saline-bouyancy 2D experiment presented here. Finally, CFD simulations using OpenFOAM software are presented, which have the goal of first reproducing measured results and then predicting performance of novel cavity designs. An initial comparison of the current SG3 receiver against a proposed reduced-aperture cavity shows the expected benefits that have come from the improved optics of the new SG4 Big Dish at ANU. CFD results will be further used in annual performance simulation to optimise receiver design in the context of the larger system.

Keywords: receiver, heat loss, convection, radiation, tubular, dish, tower, solar-thermal energy.

1. Introduction

Solar-thermal dish concentrators, such as the 500 m² SG4 Big Dish at ANU [1, 2] require a highly efficient thermal receiver able to capture and absorb the concentrated solar radiation and transfer its energy as heat to a working fluid. A design is required which maximises energy absorption while minimising re-radiation, convection and conduction heat losses. ANU is currently tackling this problem via experimental and computational studies into receiver performance. Firstly, experiments are being run based on an open electrically-heated air cavity which we can use to study effects of changes in inclination, temperature and cavity geometry on convective and radiative heat loss. Secondly, a water-based cavity experimental system has been built, in which salinity gradients drive convective flows that are analogous to those driven by thermal gradients in air. Thirdly, the original SG3 receiver (Figure 1) is now re-mounted on the SG4 big dish, and is set up to give experimental data on full-scale cavity receiver heat loss. Finally, computational fluid dynamics simulations simulations are under way to allow extrapolation of experimental data and to aid in design evaluation together, coupled with optical and radiosity modelling of the cavity receiver. The work will be extending beyond previous work [3, 4] by incorporating detailed infra-red imaging into our analysis, as well as developing some novel receiver designs not previously studied in detail.

2. Heated air cavity experiments

An electrically-heated cavity was the basis of convective and radiative heat loss studies at ANU in the past, as reported by Taumofelau [3] and similar to work at UNSW by Reynolds et al [5]. The current work is initially focussing on repeating the earlier ANU experiments, in order to benchmark the new setup against the older results. Next, new tests will be undertaken on changed cavity geometry; this will initially involve changes to cavity aspect ratio, then move on to non-cylindrical cavities and cavities with non-uniform wall heating profiles, with a goal of generating a new cavity design with significantly reduced convective and radiative losses. Furthermore, an infra-red thermal camera is being used to obtain detailed temperature maps of the interior of the cavity, which will be incorporated into heat loss studies,

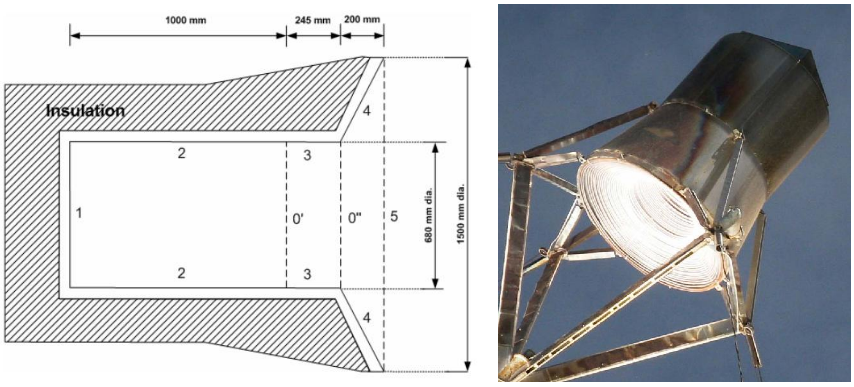

Figure 1. The original SG3 receiver is now mounted on the newer SG4 dish. This receiver is not optimised for the improved optical profile of the SG4 dish, but still provides useful data for evaluation of SG4 optics and cavity heat loss phenomena in general.

improving their accuracy and giving experimental confirmation of the size and nature of the stratified region inside a 3D open cavity receiver.

The current experimental setup is shown in Figure 2. Data is acquired by a computer running LabVIEW; thermocouples mounted inside the cavity walls report temperatures and the electrical heating (using Pyrotenax heat tracing cable) is reported via power meter, and controlled to deliver constant power. At present, a long time (at least 3-4 hours, Figure 3) is required for the rig to reach a steady-state temperature once the heating rate has been set. This reflects the fact that heat transfer through the insulation is very slow, but that there are still components, such as the external shell of the receiver, with significant thermal masses, which require significant heating before steady-state conditions are achieved.

Included in the new setup is an infra-red thermal camera. The camera is visible in the foreground of Figure 2, and a sample image is shown in Figure 4. The camera in use is an NEC H2640 with a high temperature-range sensor. The camera can record 640×480 pixel images and is sensitive in the 8–13 μm infra-red wavelength range. It is intended in this work to take images from a range of different angles and to 'stitch' them together to obtain a full temperature or radiation map of the cavity interior, for later use as a boundary condition in computational fluid dynamics simulations (discussed below). It is hoped that this will reduce (or at least identify) the discrepancies between experimental and

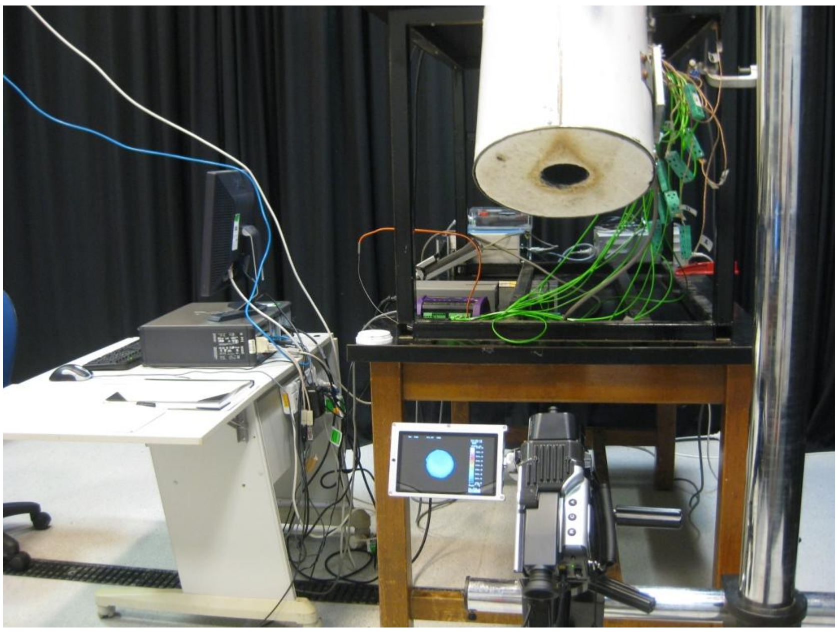

Figure 2. Air cavity receiver experiment operational at ANU. The cylindrical receiver is electrically heated and has selectable temperature and inclination angle. Initial tests are on a simple cylinder shape; further tests will alter the cavity aspect ratio and shape.

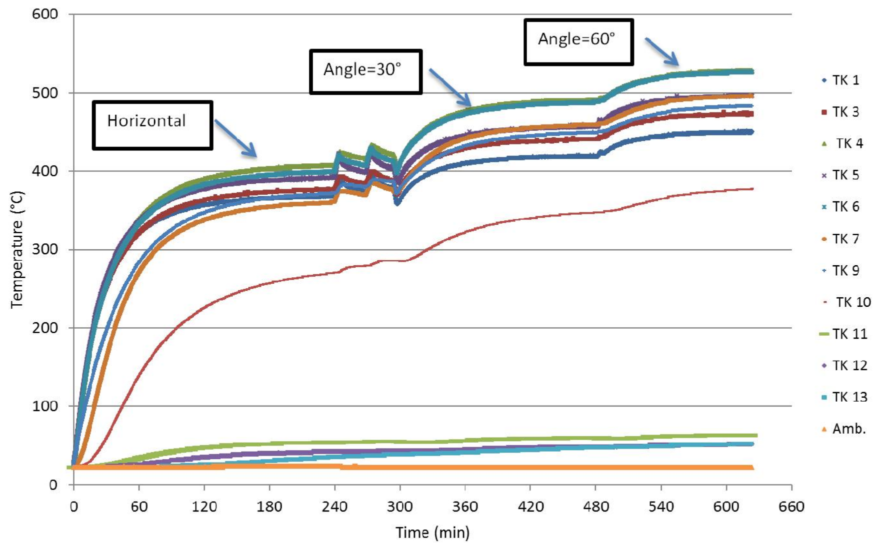

Figure 3. Long stabilisation times are required for the electrically-heated experimental cavity receiver. These long transients reflect the very low rates of heat transfer through insulation pathways relative to the thermal mass contained in those parts of the system.

simulated results. The difficulty with using a camera like this that the indicated temperatures are a function of the emissivity specified for the surface. If the emissivity is not accurate (for example, if the surface has different emissivity in different parts) then the indicated temperatures will be inaccurate. The camera has a proprietary low-level data format (.six) which prevents easy access to the raw data. Improved access to the raw data would allow more sophisticated image processing (such as automatic processing or correcting for local variations in emissivity) that is currently rather cumbersome with the bundled proprietary software.

3. Water-based cavity experiments

A new water-based cavity receiver rig has been developed. In this rig, a large tank of salt water, relatively dense, is used. A 2D cavity receiver model is immersed in the tank, and red-coloured fresh water, relatively less dense, is introduced at a controlled rate into the upper portion of the cavity. Eventually the upper portion fills up, then the lighter red fluid starts to 'overflow' from the aperture of the cavity and flow upwards towards the top of the tank. The buoyancy force in this case is proportional to the density difference in the fluid, which in this case is due to differences in salt concentration, as opposed to differences in temperature in the air cavity case. The flows are essentially analogous, subject to dimensional analysis and similarity relations. Similar work in this area was previously done at ANU by Yeh with a somewhat different experimental rig [6]. Initial results have been obtained but refinements are still required before detailed results and analysis can be reported.

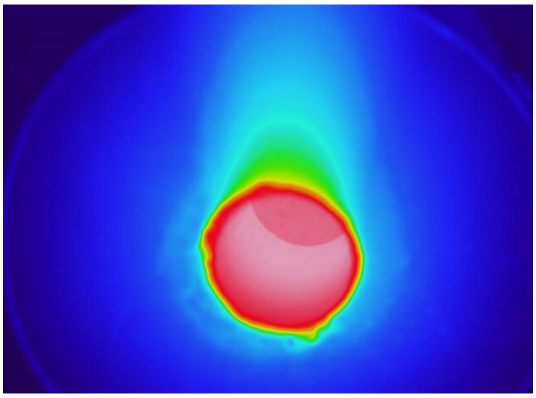

Figure 4. Thermal image of the cavity receiver. The hottest areas, in pale pink, are the cavity interior, and the local surface heating effect of the convective plume can be see above the cavity mouth (although local variation in surface emissivity plays a role in this that remains be incorporated into the analysis, see also Figure 2).

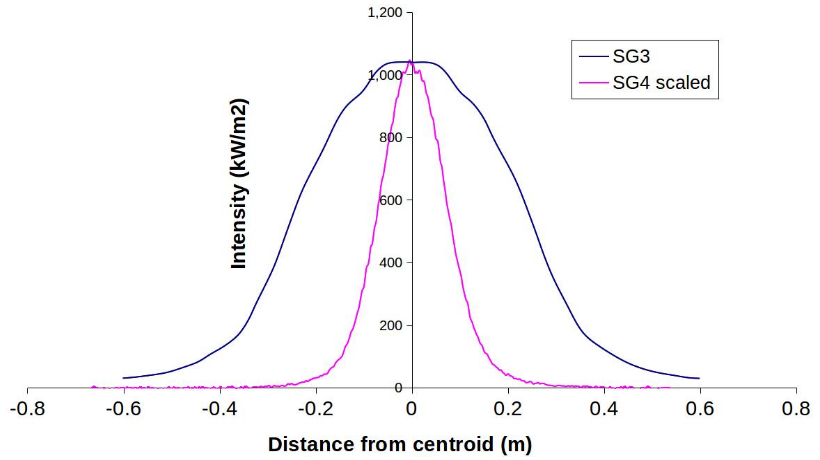

Figure 5. Flux profiles for SG3 and SG4, normalised to show the same peak intensity. The SG4 concentrator significantly improves on the earlier SG3 concentrator and we anticipate significant reductions in convective heat loss due to the opportunity to make a significantly smaller receiver.

4. CFD

Computational fluid dynamics (CFD) is a set of numerical simulation methods that can be used to simulate emergent behaviour of complex convective heat flows around arbitrary geometries. Prior studies of the SG3 receiver by Paitoonsurikarn [7] used FLUENT software for simulation of heat transfer to the surrounding air by natural convection. Related work at Sandia National Laboratories has also made use of FLUENT to study the cavity shown in Figure 2 [8]. In the current project, OpenFOAM, an open-source CFD toolkit [9], is being used. OpenFOAM is modular and extensible, and has already been demonstrated to work well on comparable problems, but is relatively unknown in the context of solar-thermal work. Being free open source software, it will be possible to modify it to suit the present needs, and it is highly scalable at minimal cost.

Some initial results from work using OpenFOAM to simulate the heat transfer, for (a) the SG3 cavity and (b) for a proposed cavity reduced-aperture receiver, are presented here. The SG3 cavity aperture diameter, as constructed and currently mounted on the SG4 dish at ANU, is 680 mm. The reduced aperture diameter considered is 540 mm. An optimised receiver diameter is still being determined, however based on experimental work to date [10], it is expected that a cavity of this 540 mm diameter (or smaller) will be achievable due to the significantly improved optics in the SG4 collector. Flux profiles of the SG3 and SG4 collectors are compared in Figure 5. Through the use of a reduced-aperture cavity, the radiative and convective losses will be reduced due to a reduction in internal surface area and reduction in view factor from this surface to the cavity aperture.

Figure 6 shows the preliminary values for the convective heat loss determined for OpenFOAM simulations for each cavity, inclined horizontally. For the reduced-aperture cavity shown on the right, the size of the front frustum was reduced proportionally to the aperture reduction, and the length of the cavity was left unchanged. The internal cavity walls are uniform in temperature, fixed at 450°C. The Figure shows the surface mesh of the cavities, then the temperature fields both inside the cavity and in the outside 'plume'. Finally, for each cavity, there is a plot of the heat transfer from the interior walls, as a function of time. The plots show the dynamic OpenFOAM solver attaining steady-state convective heat loss after 10s-15s of operation for each case.

The simulated steady-state convective heat loss for the SG3 receiver is 7.50 kW at 450 °C, which corresponds to a heat loss per unit area of 2.57 kW/m^2, which is 16% lower than the value calculated by Paitoonsurikarn [4] for the same cavity case. For the reduced-aperture cavity, the simulated heat loss is 5.90 kW at steady state, 21% lower than the result for the SG3 receiver. The per-area heat flux is not greatly changed, at 2.52 kW/m^2, suggesting that cavity receiver heat loss at constant temperature is approximately proportional to receiver internal area: it appears that changes in heat transfer coefficient are going to be second-order compared to the effect of overall reduction in internal cavity area. Further work is under way to more thoroughly validate the OpenFOAM numerical results; simulations will then proceed to consider other variations in cavity geometry, including non-cylindrical cavities, and modified frustum configurations. It is intended that improved dimensionless cavity receiver heat loss correlations be developed as an extension of the work by Paitoonsurikarn et al [7], by specifically incorporating into the correlation the geometric dependence of the depth of the stratified region on the inclination angle.

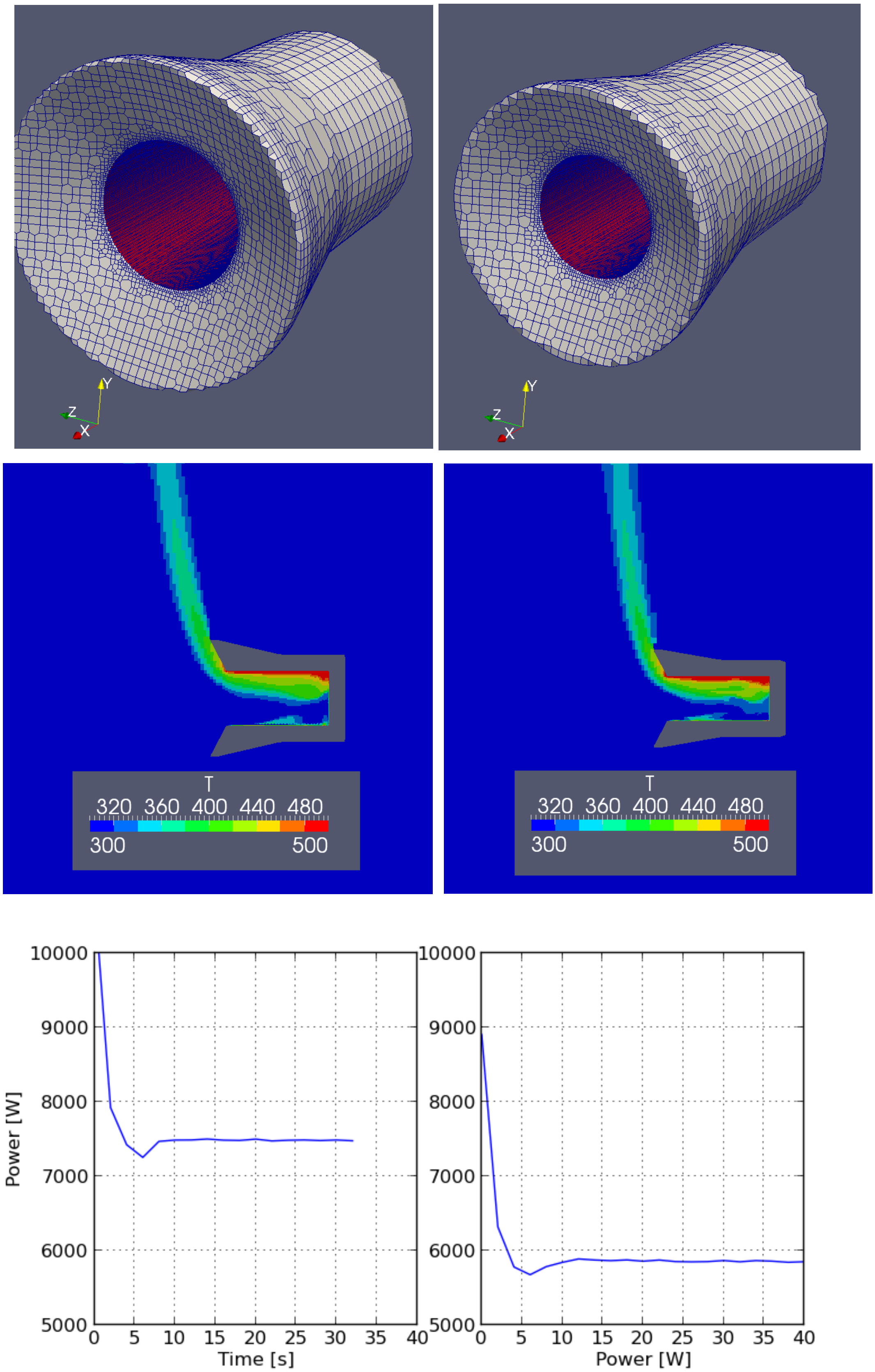

Figure 6. Current SG4 Receiver geometry (top,left). Proposed SG4 Receiver Geometry (top, right). CFD snapshot of buoyant flows after 30s of operation from current (middle, left) and proposed (middle, right) receiver geometries. Total heat flux as a function of time from cavity-inner wall for current (bottom, left) and proposed (bottom, right) cavity receivers.

5. Conclusions

Early-stage results have been presented for experimental and computation work at ANU on a project that aims to increase the efficiency of tubular open-cavity receivers on dish concentrators. Lab-scale measurements have been gathered including thermal imaging, and computational work with OpenFOAM is underway. Validation is still in progress, both for the experimental as well as the computational work.

Acknowledgements

We thank the Australian Solar Institute for their support in funding this project, and Tania Ritchie and Sarah Miller at CSIRO Energy Centre for the generous loan of the infra-red camera.

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