PARABOLOIDAL DISH SOLAR CONCENTRATORS FOR MULTI-MEGAWATT POWER GENERATION

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Abstract – Solar Thermal research and development began at the Australian National University in 1971. A prototype 400m^2 solar dish was completed in 1994. The focus of the R&D efforts remains on the development of distributed dish, central generation solar thermal power systems using either direct steam generation or ammonia based thermochemical energy storage. Current work includes the re-commissioning of the 400m^2 dish system after some years of inactivity, investigation of convection losses from receivers, transient simulation using TRNSYS, development of improved mirrors and other components, plus an ongoing investigation of a thermochemical energy storage loop based on ammonia dissociation. Overall, the technology is ready for a first multiple dish commercial demonstration system.

1. INTRODUCTION

Solar Thermal research and development began at the Australian National University (ANU) in 1971. The early work lead to the design and construction of the 14-dish, steam-based, solar thermal power station in White Cliffs (Kaneff 1991). A parallel line of investigation lead to the pioneering work on ammonia-based thermochemical energy storage Carden (1977). A major milestone has been the completion in 1994, of the 400m^2 dish concentrator prototype, shown in Figure 1.

The focus of the R&D efforts remains on the development of distributed dish, central generation solar thermal power systems using either direct steam generation or ammonia based thermochemical energy storage.

Work continues on all important aspects of the technology, including the re-commissioning of the 400m^2 dish system after some years of inactivity. Laboratory tests and Computational Fluid Dynamics (CFD) modeling are being used to investigate convection losses from dish receivers. Transient simulation of dish based solar thermal plants using steam is being investigated using the transient simulation package TRNSYS. Improved mirror panels and other components are being developed. Plus investigation of a unique thermochemical energy storage loop based on ammonia dissociation continues.

This paper provides an overview of these activities.

2. THE ANU 400m^2 DISH SOLAR CONCENTRATOR

The structure of ANU's 400 m^2 paraboloidal dish solar concentrator, shown in Figure 1, is based on a space-frame design with a network of tubular steel members joined to spherical nodes. The dish rotates on a reinforced concrete track. Fifty-four triangular mirror elements are attached to the dish-frame. The mirrors used on the ANU prototype, deliver a peak concentration ratio of 1500 (Johnston 1995).

A monotube boiler housed in a "top-hat" cross section cavity receiver produces up to 100 g/s of steam that is

Figure 1: 50 kW$_e$ prototype solar power plant using ANU's 400 m^2 paraboloidal dish.

superheated to typically 500°C at 4.5 MPa. This steam is passed to the ground via steamline and rotary joints for expansion in a grid-connected steam engine / generator unit. Table 1 provides some basic design information about the system (Caddet 1999). ANUTECH Pty Ltd (the ANU's commercial arm) has supplied a similar 400 m^2 "Big-Dish" unit to the Sede Boqer campus of the Ben Gurion University in Israel (Biryukov 1999).

The prototype on the ANU campus in Canberra, has been inactive for a number of years while the group concentrated on other projects and organisational aspects within the university were finalised. At the end of 2002 it was re-commissioned and now operates on a regular basis. Re-commissioning required upgrading the mains electrical wiring and other aspects to meet the applicable codes and the university's Operational Health and Safety guidelines. In addition some de-bugging of the actuation system was required. The steam system and mechanical components however, remain fully functional after 9 years.

Table 1: Design details of ANU's 400 m^2 dish / 50 kW_e steam engine system.

Dish	
Aperture	*400 m^2*
Rim angle	*46.6°*
Focal length	*13.1 mr*
Mirror reflectivity new	*86 %*
Tracking envelope	*Elevation: + 5° to + 90°; Azimuth: ± 210°*
Concentration ratio	*84% above 1000-sun (0.25° tracking error)*
Design weight	*Dish - 19 tons, foundations 50 tons*
Receiver	
Design	*Monotube cylindrical boiler*
Operation envelope	*400 - 600°C; 4.2 - 6.8 MPa*
Design output	*320 kWth*
Thermal efficiency	*80% - 90%*
Engine / Generator	
Generator	*65 kVA ansynchronous*
Efficiency	*18.6%*

1.1 Actuation system

The dish utilizes an altitude/azimuth tracking system, with movement on each axis being provided by a hydraulic ram. These rams do not have sufficient extension to provide the full movement through the required range. Instead a patented "walking ram" concept is employed (Whelan and Kaneff 1995). Once a ram has reached the limit of its extension or retraction a solenoid controlled pin which attaches it to the structure is released, and the ram is then free to retract or extend, respectively, until the next engagement point is reached. During this process a lock pin is engaged to hold the dish in a fixed position on that axis.

A three-phase electric motor drives a Vickers piston pump to provide the required hydraulic pressure (up to 12 MPa), with an average electrical power consumption of less than 1kWh per hour.

A commercial controller system (Opto 22™) is used to calculate the sun position (open loop tracking), monitor the dish position and the state of various transducers, and control the solenoid valves which determine the dish movement. The system comprises Cyrano 200 (R3.1a) software running on a PC, a G4LC32SX Mistic processor, and G4 series I/O modules. The Mistic processor can perform all functions independently of the remote PC, however the latter is generally used in the prototype system to allow the operator manual control of dish operation if desired.

During the re-commissioning period the control software has been revised and extended, with the general goal of making the system as robust as possible and obviating the need for operator intervention. Some modifications to the actuation system have also been made, also with the aim of making the system more reliable: position transducers were formerly used on the azimuth axis to guide the walking ram to the next engagement position (which consists of a hole in a steel anchor mounted to the concrete base). This method suffered from hysteresis and other errors and the hole was occasionally not located with sufficient accuracy for the pin to engage. Inductive proximity are now used to sense the metal anchor and thus the hole.

1.2 Mirror panels

The mirror panels on the prototype dish consist of 3mm mirror glass held in place on galvanized sheet steel frames, by a filler of polyurethane foam. They were hand made at the university and do not represent a design that would suit mass production. Subsequently it was found that in some areas, poor quality control in the mixing of the foaming resin, resulted in the resin attacking the backing paint on the mirrors and subsequent corrosion and loss of some of the mirror surface.

A new solar reflector technology based on the application of thin, back-silvered, low-iron glass permanently bonded to a thin sheet metal substrate (termed Glass on Metal Laminate – GOML) has been developed. Accelerated-lifetime tests over the past 3 years have proven the durability of this technique.

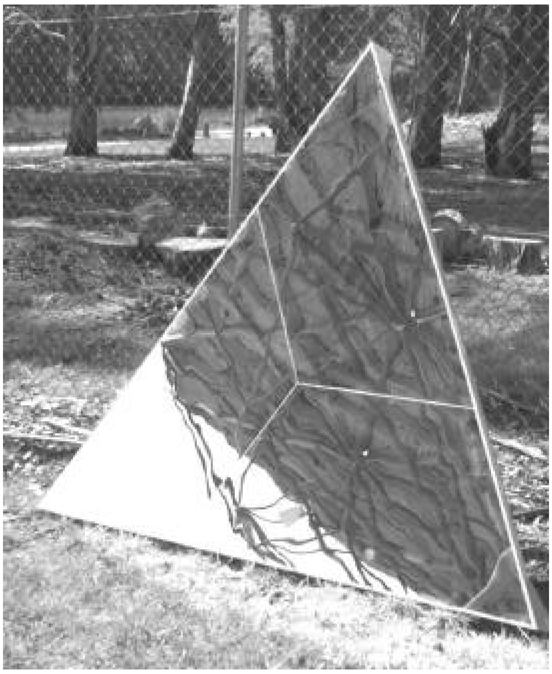

Figure 2: Triangular prototype GOML solar reflector element for ANU's 400 m^2 dish.

This has been coupled with a new mirror panel structural design that is optimized for mass production. Figure 2 shows a triangular prototype GOML solar reflector element for ANU's 400 m^2 dish.

A key element in the new design is that by making the panels smaller (increasing the number to 324 per dish), they can all be made with an identical radius of curvature and still achieve acceptable optical performance (Johnston 1996)

It is planned to fit a full set of the new panels to the dish when the resources become available.

1.3 Performance

Steady state performance measurements carried out in the period immediately after the dish was completed showed receiver thermal efficiencies in the range 80-90%

Determination of losses (combining optical and thermal losses) from the receiver during recent tests, yielded the results in figure 3. Since the focal region flux distribution has not been mapped recently it is not known how much of this can be attributed to any deterioration in mirror shape.

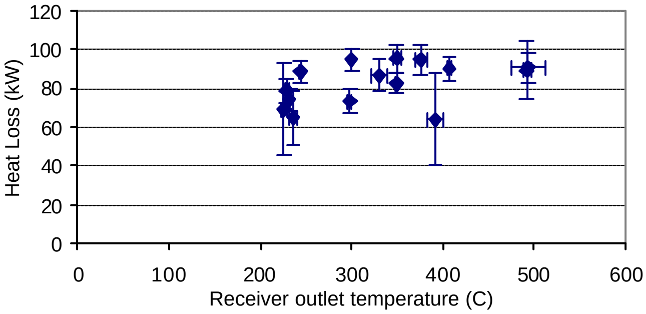

Figure 3. Recent measurements of combined optical and thermal losses for the ANU 400m^2 dish system.

If the mirrors were replaced with a full set with 92% reflectivity, operation under 1000Wm^{-2} insolation with losses in this range would give receiver efficiency in the range 70 – 80%, lower than the original measurements, suggesting that some loss of optical quality has also been experienced in addition to the loss in effective mirror area.

3. RECEIVER CONVECTION LOSS

In solar energy thermal systems, heat loss mechanisms can significantly reduce the efficiency and consequently the cost effectiveness of the system. With parabolic dish cavity receivers, conduction and radiation losses can readily be determined analytically, however the complexity of the geometry, temperature and velocity fields, in and around the cavity makes it considerably harder to determine the convection loss.

There have been several previous investigations of convection losses from cavity receivers. A model of large cubical central receivers was proposed by Clausing (1981), based on the local convective heat transfer coefficients inside the cavity, determined from standard semi-empirical correlations and the energy transferred by the air through the aperture due to buoyancy and wind effects.

Eyler (1980) examined the convective heat loss from the rectangular cavity numerically and found a non-linear dependence of heat loss with respect to inclination angle.

Experimental studies by Koenig & Marvin (1981) and Stine & McDonald (1989) explicitly included parameters such as inclination angle and aperture size into their empirical models.

Leibfried et al (1995) developed two generalized models that can be used for both downward and upward facing cavities with various geometries. The two proposed models were based on modifications of the work of Clausing and Stine & McDonald respectively.

3.5 Experimental Investigation

An electrically heated experimental simulation of a cavity receiver has been constructed to allow direct measurement of losses under laboratory conditions. The details of the arrangement are shown in figure 4. The model receiver consists of a mild steel tube cavity with a "Pyrontenax" mineral insulated electrical heater cable wound around it as a source of heat input. The cavity interior surface has been painted with high temperature resistant black "Pyromark" 2500 paint. The steel tube is mounted in a framework of Calcium Silicate insulation board. The entire structure is covered by a sheet metal casing and all internal spaces filled with "Kaowool" ceramic insulation material.

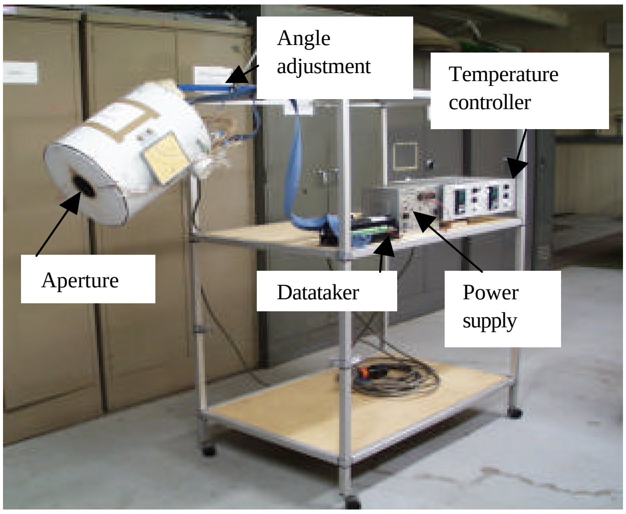

Fig. 4 Experimental setup for laboratory investigation of convection losses.

The receiver model is attached to a hinged angle adjustment mechanism to enable testing at different angles. There are 7 type K thermocouples that measure the cavity surface temperature, 8 on the exterior surface of the model, plus a further 8 measuring various temperatures within the model. These thermocouples are logged with a Datataker 600. The temperature of the cavity is controlled by a Eurotherm 808 PID temperature controller that regulates the power level to the heating coil. A host computer, not shown in figure 4, acquires both the data from the Eurotherm temperature controller and the Datataker.

During operation, a time interval of approximately one hour is required for the system to reach steady state. Temperatures and power level are logged at five second intervals for a period of 30 minutes, to provide the data for a reliable steady state data point. A "Fluke 83" multimeter is used to measure the supply voltage *V*, and heater resistance *R*, and in conjunction with the regulated power level, the total heat loss rate from the receiver is determined.

Since it is convection loss that is of interest, conduction and radiation contributions need to be accounted for. To determine the conduction heat loss, measurements of loss were made with the cavity inverted and with an insulated plug in the aperture. It is assumed that conduction is the same for all inclination angles.

Radiation loss has been determined analytically with the network method described by Holman (1997). An emissivity of 0.85 was used for the "Pyromark" painted cavity surface. With the high emissivity of the paint, the uncertainty in an effective emissivity at the aperture is negligible.

Figure 5 presents the results of heat loss measurements using the model receiver operating at a set point temperature of 450^{o}C.

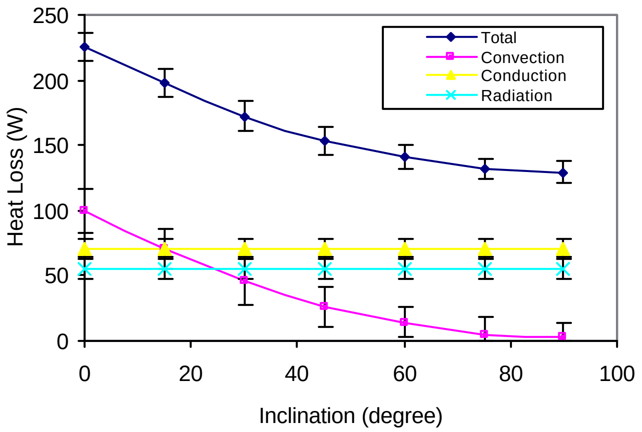

Figure 5. Experimental heat loss for a cavity temperature of 445^{o}C.

Conduction losses were measured to be constant at 70.8 ± 9.7 W and radiation losses calculated at 55.7 ± 8.0W. The maximum convection loss occurs at 0^o (receiver in a horizontal position) when it represents 43.9% of the total heat loss. As is expected, the minimum convection loss occurs when the receiver is pointing vertically downward (90^o) representing 2.2% of the total heat loss. In this orientation, the high temperature buoyant air remains stagnant within the cavity. It is worth noting though, that the convection losses are not zero at 90^o inclination, as suggested by some models.

3.5 CFD Modelling with FLUENT

The CFD Software Package, Fluent 6.0 (Fluent Inc., 2002) is being employed in the 3D simulation of the natural convection through the aperture of the cavity receivers.

In reality, a receiver is surrounded by an infinite atmosphere with a limiting temperature equal to ambient air temperature. In the CFD analysis, this needs to be approximated by placing the receiver in a sufficiently large enclosure with walls at ambient temperature. It was found that the diameter of the cylindrical enclosure should be about twenty times the diameter of the receiver to have an insignificant effect on fluid and heat flows in the vicinity of the receiver.

Grid dependency was investigated and the final grids used consist of approximately 2x10^5 hexahedral cells. The cells are very small in the region inside the cavity and nearby the receiver but increase in size gradually toward the cylindrical enclosure wall. Figure 6 shows typical grids used for the laboratory model and 400 m^2 dish receiver cases.

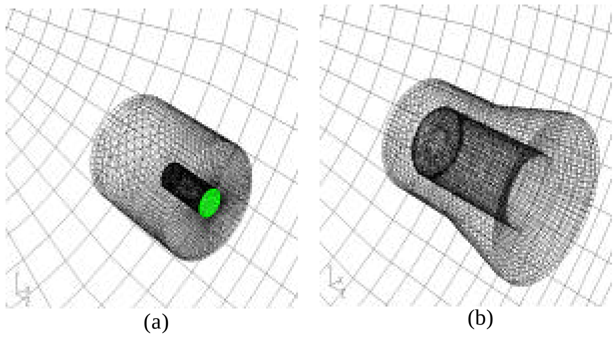

Figure 6. Typical computational grids for (a) model receiver and (b) 400 m^2 dish receiver.

The flow and heat transfer simulation is based on the simultaneous solution of the system of equations describing the conservation of mass, momentum, energy and turbulent transport property. The Spalart-Allmaras one-equation turbulent model recommended by Spalart (2000) is employed.

An Isothermal boundary condition was applied to cavity wall, whereas the outer walls of the receivers were assumed to be adiabatic.

An example of a predicted flow pattern is shown in figure 7.

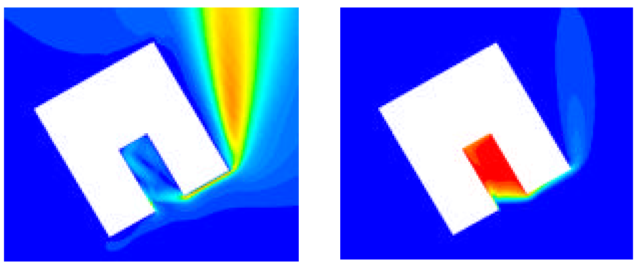

Figure 7. Contour plots at symmetric plane for model receiver at 60^o inclination: (a)- velocity magnitude, (b) temperature.

It is evident that the predicted flow pattern is in agreement with what is intuitively expected. The similarity between velocity and temperature profiles indicates the strong coupling between momentum and energy in natural convection. A relatively stagnant core is observed in the middle of the cavity

The experimentally measured convective heat loss from the model receiver is plotted in Figure 8 together with the results from the CFD calculations and the values calculated from correlations presented the various authors previously discussed.

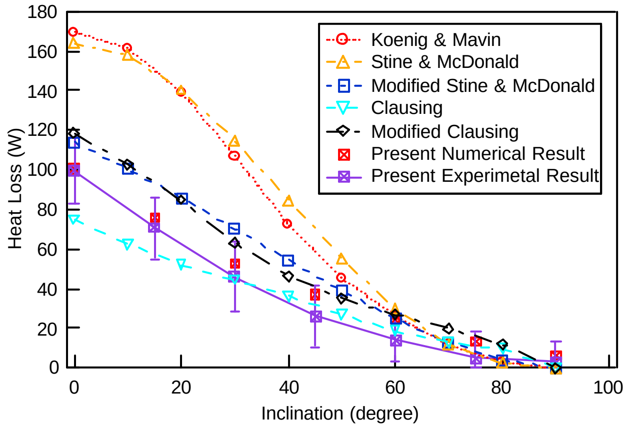

Figure 8. Comparison of natural convection heat loss through the aperture for model receiver.

It is apparent that the CFD calculation agrees with experimental measurement within corresponding measurement uncertainty. However, it tends to overestimate experimental result at all angles of inclination, especially at intermediate angles.

Although all the correlations show qualitatively the same dependence of heat loss on angle, there is a significant spread in magnitude.

The Koenig & Marvin model and Stine & McDonald model predict the heat losses with the greatest deviation from the present results and those predicted by other models. This might be due to the fact that both were derived from the results obtained with actual receivers whose length scales were much greater than that of the model receiver. However, the Clausing model shows the best agreement with the present result despite the fact that it was primarily derived in the application of central receiver. The modified Clausing and Stine & McDonald models proposed by Leibfried et al (1995) are comparable to each other and relatively close to the present results but not as close as the original Clausing one.

All of the correlations examined predict zero natural convective loss at 90^o angle. This is physically implausible and indeed both the experimental measurements and CFD calculation from this study indicate that this is not the case.

CFD calculations have also been applied to the geometry of the cavity receivers on the ANU 400m^2 dish. The results of flow and heat transfer characteristics for both are qualitatively similar to those of the model receiver.

The calculated heat losses are plotted in figure 9, together with the predictions of the various correlations identified.

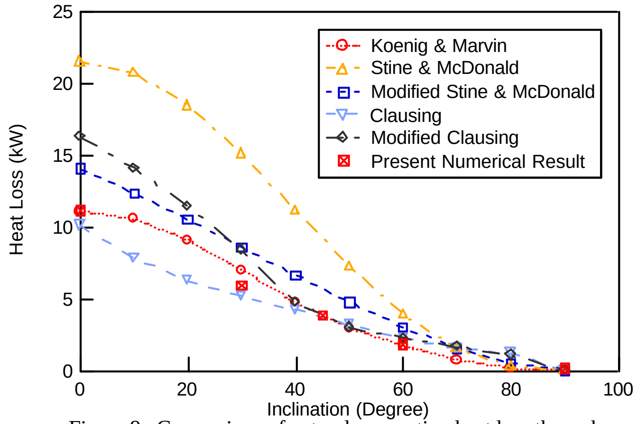

Figure 9. Comparison of natural convection heat loss through the aperture for 400 m^2 dish receiver.

Considering the uncertainty quoted in each correlation, the comparison shows that, despite their actual range of applicability, all correlations except the Stine & McDonald predict the convective heat loss within a similar range and hence might be used interchangeably. Nonetheless, the Clausing model is recommended as it can best correlate both the experimental and numerical data in all three cases considered.

The final goal with the work is to develop an improved correlation that can reliably predict natural convection losses from cavity receivers on dish concentrators at all angles. The approach taken has been to use a relatively standard correlation form, but to look for a characteristic length scale that combines diameter, depth and angle in a manner that provides an overall universal best fit. The expression currently considered is:

$$Nu = 0.004 \cdot Ra^{0.44} \cdot \left(\frac{D_{ap}}{D_{cav}}\right)^{0.03} \cdot \Pr^{0.25}$$

Where;

Nu =Nusselt number

Ra=Rayleigh number

Pr=Prandtl number

D_{ap}=Aperture diameter,

D_{cav}=Average cavity diameter

The characteristic length scale that best fits results to date is:

$$L_S = \left(2.05\cos^{3.27}(f) - 0.06\sin^{0.66}(f)\right)D_{cav} + \left(6.42\cos^{5.27}(f) + 0.03\sin^{0.13}(f)\right)L$$

Figure 10, compares the predictions of this correlation with the CFD and experimental results and indicates good agreement so far.

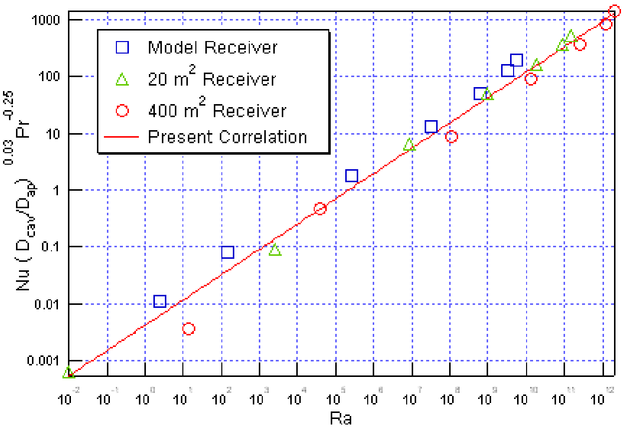

Figure 10. Comparison of prediction by the present correlation and numerical results of three receivers.

4. TRANSIENT SYSTEM MODELLING

Solar Thermal Power plants have components with thermal time constants that can be minutes or even significant fractions of an hour. As a consequence, a reliable prediction of a real plant's annual performance, requires an accurate transient system model.

Simulation of dish based solar thermal plants using steam is currently being investigated using the transient simulation package TRNSYS (Uni of Wisconsin 2000). TRNSYS together with the user interface IISiBat, offers many features; including the availability of libraries of existing simulation components, the capability of interconnecting system components in any desired manner to accomplish a specified task and especially user friendly tools to facilitate the creation of custom components.

A Solar Thermal Electric Component (STEC) model library for TRNSYS has been created under the SolarPACES umbrella by DLR Köln and Sandia. (Pitz-Paal and Jones 1999). The STEC library includes models for Rankine cycle, Brayton cycle, solar thermal receivers, parabolic trough, condensers amongst others. Previous work at ANU has developed new components application to ammonia based thermochemical energy storage systems using dish concentrators. This has included a paraboloidal dish component (Type 251), a reactor component and a thermochemical receiver component.

The current work is looking at the simulation of Direct Steam Generation (DSG) dish receivers in the context of multiple dish, central generation Rankine cycle power plants. The type 251 dish component is being used, it produces the aperture area and incident solar power for a receiver, using rim angle, slope error and dish collector area, provided by a user supplied data table. To date the component has been used to simulate the ANU $20m^2$ and $400m^2$ dish systems. Components to model a DSG receiver and an element of steamline are currently under development. The receiver component models the true transient behaviour of a DSG receiver. It solves the energy balance taking into account the thermal mass of the receiver tubes and the movement of the boiling zone and subsequent variations in exit mass-flow in response to insolation variations.

Figure 11 shows some encouraging preliminary results obtained for a simulation of the $400m^2$ dish and receiver geometry.

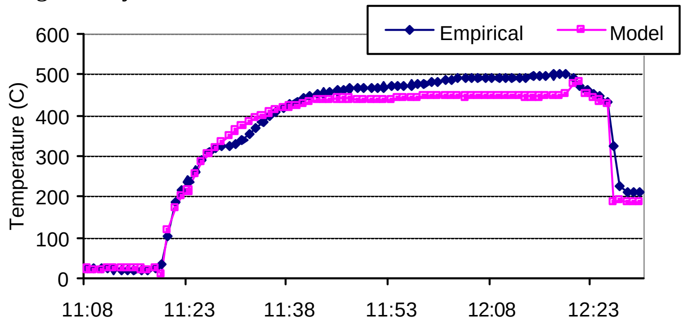

Figure 11. Comparison of experimental and modelled receiver exit temperature for 9 Jan 2003. Dish on the sun from 11.18–12.19 with approximately constant $1000Wm^{-2}$ insolation.

5. AMMONIA BASED THERMOCHEMICAL ENERGY STORAGE

Whilst steam based systems offer the most practical short term route to commercial demonstration of the dish technology, thermochemical energy conversion offers the prospect of continuous baseload and demand following power generation. The ANU group is currently operating a closed-loop, ammonia-based thermochemical energy storage system using a 20 m^2 paraboloidal dish concentrator (Lovegrove et al 1999). The concept is illustrated in figure 12.

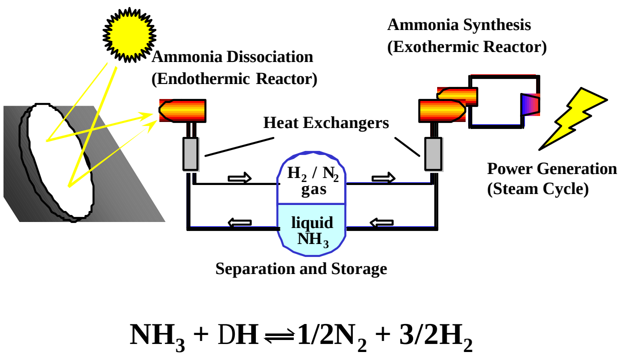

Figure 12. Thermochemical storage of solar energy by ammonia dissociation.

A significant milestone achieved in May 2002, was operation of the closed loop system continuously for 24 hours.

The solar ammonia dissociation receiver/reactor consists of twenty 0.5m long Inconel tubes positioned in a conical arrangement inside the insulated cavity. At the apex, the tubes are tied to disk-shaped inlet and outlet manifolds. The tubes are filled with a triply-promoted iron-cobalt catalyst ('DNK-2R' by Haldor Topsøe). The measured energy storage efficiency of the receiver is 63%.

The success with the receiver design motivated a scale up design for use on 400m^2 dish that simply involves using more reactor tubes of the identical design, but increased in length to 1m. Laboratory investigation of the performance of more active Ruthenium based dissociation catalysts is also being investigated. These offer the prospect of achieving the same levels of conversion at lower receiver temperatures and consequently reduced thermal losses.

6. MULTIPLE DISH POWER SYSTEMS

The vision behind the steam or thermochemical approaches to energy conversion, is the construction of systems comprising distributed arrays of dishes, feeding the collected energy as either steam or reaction products, to a central large scale power generation plant.

Table 2, presents predicted data for a hypothetical steam based systems of 2 MW_e (Luzzi 2000) and 20 MW_e project (Kaneff 2000). A net solar-to-electricity conversion efficiency of around 30% should be achieved with the dish-based DSG technology once it matures toward a megawatt-scale steam turbine system with multiple-dish solar collector field.

Table 2: Performance estimates for a 2 MW_e and a 20 MW_e steam turbine based system at 1000Wm-2 insolation.

	2 MWe System	*20 MWe System*
Solar power intercepted by each absorber / receiver	*335 kWrad*	*346 kWrad*
Solar power absorbed by the feedwater in each boiler	*301 kWth*	*318 kWth*
Equivalent heat rate to the steam engine or turbine	*280 kWth*	*299 kWth*
Gross electricity generated (specific per 400 m2 dish)	*95 kWe*	*110 kWe*
Net power generated per 400 m2 dish concentrator	*92 kWe*	*108 kWe*
System net solar-to-electricity conversion efficiency	*~ 23%*	*~ 27%*

By 1994, the manufacturing and erection costs of the 50 kW_e prototype solar thermal dish / engine system in Canberra amounted to about AUD 0.6 million (Sinclair Knight Merz 1998). A 2 MW_e demonstration project based on 18 ANU dishes has been detail-engineered by a construction company in 2000 and offered on a turn-key basis at a specific cost of around AUD 6 million per MW_e (Luzzi 2000). The costs for a single, fully-commissioned 400 m^2 DSG-dish with associated feedwater / boiler / steam system and dish controls are close to AUD 0.4 million.

System costs for a first 20 MW_e turn-key power plant (based on 200 dishes) are estimated at AUD 4 million per MW_e, with specific DSG-dish costs of about AUD 0.28 million. Operated, maintained and depreciated over a period of 20 years, this would lead to specific power generation costs of the order of AUD 0.12 – 0.16 per kWh, depending on the competitiveness of financing and choice of site.

A previous study of a 10MW_e ammonia based system (Luzzi et al 1999), suggested that generating costs very close to those of a steam based system could be achieved for a plant with the added advantage of 24 hour operation.

5. CONCLUSIONS

The ANU's prototype 400m^2 solar dish was completed in 1994. The group continues to work on improvements in the design, particularly the key component of mirror panels. Development and verification of transient system models provides essential information for predicting the annual output to be expected from commercial systems. Detailed understanding of receiver thermal losses will lead to performance improvements. In the longer term, steam based energy conversion can be substituted by ammonia based thermochemical conversion allowing 24 hour production of electric power. Overall, the technology is ready for a first multiple dish commercial demonstration system.

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