First Results from Compact Linear Fresnel Reflector Installation

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Abstract

Stage 1 of the Compact Linear Fresnel Reflector (CLFR), a linear-concentrating solar thermal energy system at Liddell Power Station was completed in June 2004 and first performance results have been obtained. Direct steam generation (DSG) within the solar array has been achieved to milestone specifications and optical performance has met the design specifications.

1. INTRODUCTION

Fig. 1. The Phase 1 CLFR array in operation at Liddell power station.

This paper describes the testing of a 1MW(th) on-site Compact Linear Fresnel Reflector (CLFR) solar array at Liddell Power Station (Fig. 1). The solar array concept used in this project is of the Linear Fresnel type and was originally developed at the University of Sydney in 1993 (Mills and Morrison, 2000). In the present more advanced approach, ground level reflector rows aim solar beam radiation at a downward facing cavity receiver mounted on multiple elevated parallel tower lines. The technology is innovative in that it allows reflectors to be focused on either of the adjacent absorber lines so that a configuration can be dynamically chosen by the control system which offers minimal mutual reflector blocking.

The system is low-cost by virtue of the off-the-shelf components chosen for its construction. The mirror tracking structure is crucial to the low cost of the design: mirrors are bonded in an elastically deformed state onto a sheet of standard corrugated roofing steel. The steel roofing sheet is then mounted on a simple space-frame with support and tracking hoops placed every 12 metres. The hoops are set upon rollers which allow 360° rotation. Projected electricity generation costs for large stand alone systems using thermal storage are close to fossil fuel generation cost (Mills et al, 2004).

Stage 1 is the first phase of a three-phase solar coal saver project aimed at the installation of a solar array capable of supplying more than 100 MW (thermal) of solar heat to the feedwater heaters of a 500 MWe turbine at Liddell Power Station. Not only is this coal saver a viable project niche, but it allows collector technology to be proven before going to stand alone solar plants.

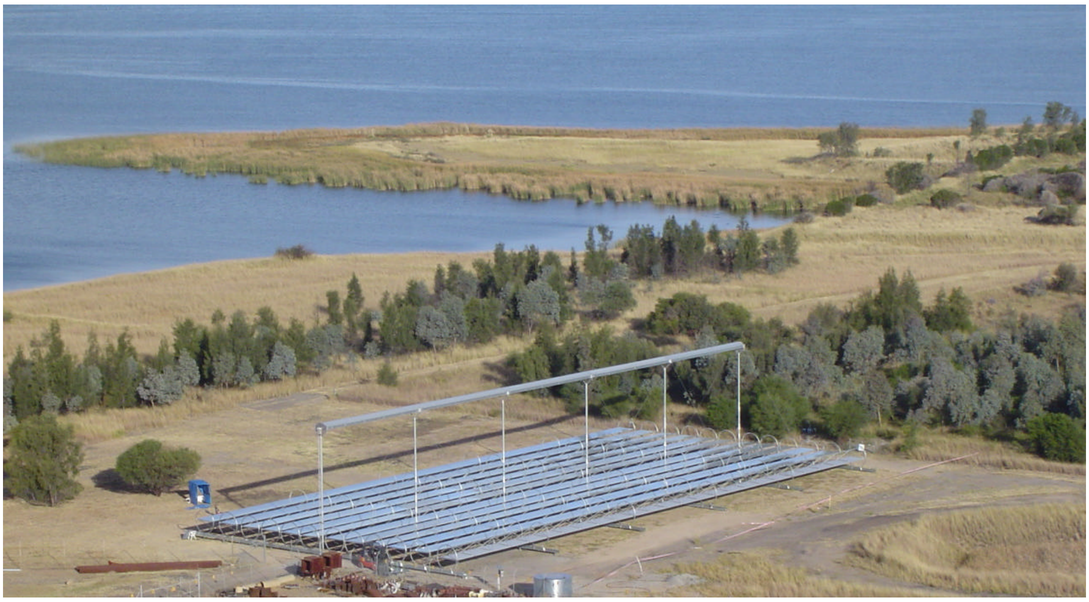

Fig 2. Aerial view of Stage 1 nearing completion. In Stage 2 the array will be extended by a factor of ten to both to the west and the south for a net of 100 times the coverage shown.

Stage 1 consists of 1350 m^2 of reflector modules and a single short elevated absorber line 62 m long. Each absorber line is straddled by 12 reflector rows using glass reflector 1.84 m wide. Stage 2 will consist of three absorber lines each 300 m long with 20,000 m^2 of reflector and stage three will use 20 x 300 m absorber lines with a total reflector area of 135,000 m^2. Stage 1 is only 1% of the final array, and is located in the north east corner of the eventual Stage 3 array (See Fig 2).

Stage 1 was built to test the performance of the design against the simulated performance prior to a Stage 2 rollout. During the preliminary testing, solar radiation, steam or water output temperature and pressure, and feedwater flow rate were measured. Two primary measurements were required in Stage 1 before proceeding to Stage 2:

1. Optical efficiency measurement achieved by operating the absorber at low temperature using water as the heat transfer fluid.
2. Demonstration of stable steam production at 285°C and 69 Bar, the anticipated operating conditions of the solar array.

2. MODELLING

2.1. Description

Array performance was required to validate a performance simulation model used in the preliminary design. A solar modelling program with a raytrace model was used to provide primary collector optical data for subsequent thermal simulations.

Because of the short length of the Stage 1 array, a significant portion of the absorber line was not illuminated during the July/August test period. The length of the absorber not illuminated is different for each reflector row, and for the time of day and date, but is completely predictable. The non-illumination was calculated for each time of day of the experimental trials and this is included in Table 1 under the heading “Unilluminated Absorber”. The method used to calculate the end effect is described in Buie et al. (2002).

While the unilluminated section of the short absorber of Stage 1 is relatively large for these mid-winter trials, the illumination is close to 100% in mid-summer and would be insignificant on the main array, in which two 300 m long absorber lines are mounted end to end and fed from a central header. Thus, in Stage 3, the worst case unilluminated condition would be about 4% in winter over the day and almost zero in summer. The effect is non-linear with season however, the end effect would be about 1.8% over the year. However, these effects are only calculated optically; because of the thermal starting threshold, the end effects at the beginning and ends of the day are not so important and the average annual performance loss may be slightly diminished. The performance loss can be eliminated by extending the reflector field slightly.

Solar radiation and thermal models of the CLFR collector were developed in the TRNSYS (version 15) modelling environment. TRNSYS is a transient system simulation program designed to analyse any transient thermal process. For this project a series of modelling extensions in TRNSYS were developed to simulate the compact linear Fresnel concentrating collector receiver and system (Pye et al. 2003; Reynolds et al. 2002 and 2004). The steam conditions in the absorber are analysed in a separate model of two phase flow in the long absorber tubes. The primary routines that were used to simulate the CLFR solar collectors are described in the following two sections.

2.2. Radiation processor

The nonisotropic radiation distribution model in TRNSYS was used to compute beam and diffuse radiation components from weather data for Williamstown. Satellite data was used to scale the radiation data from Williamstown to Singleton.

2.3. Linear Fresnel solar concentrator

To model the optics of the CLFR, the TRNSYS collector routine was modified to include specification of optical concentration through a biaxial incidence angle modifier map. This was implemented via an extension of the optical mode 4 option in the TRNSYS solar collector model. The new routine was designed to accept an incidence angle modifier map with up 50 incidence angles in both the longitudinal and transverse planes. The optical map data was generated by ray tracing carried out separately from the TRNSYS model.

The collector thermal mass was modelled in TRNSYS using an instantaneous collector efficiency model coupled to a zero heat loss storage tank. This procedure used the proven TRNSYS tank routine and the TRNSYS iterative solver to include the effect of thermal capacitance rather than developing a complex collector model with built-in capacitance. This model follows the start up and shut down transients at the beginning and end of each day and transient effects during cloudy periods. These transient effects, due to thermal capacitance within the absorber, were found to reduce the annual output of the collector array by less then 3% for array concentration greater than 20.

3. EXPERIMENTAL RESULTS

3.1. Optical Trial

The array was tested in mid-winter rather than mid-summer, and, consequently, performance is considerably reduced at this time of year because of the cosine effect (the solar beam is coming in at a large angle rather than more normal to the array as in mid- summer). However, this effect can be predicted in the collector modelling programs and the performance extrapolated to summer and other times of year.

Typical measurements of the prototype system performance are shown for the 28th July and comparisons have been made between the measured and predicted system efficiency for July conditions. The measured performance is shown in Fig. 3 and a comparison with the predicted performance is included. The efficiency calculated from the measurements was corrected for end effects in the short prototype system as previously described (see Table 1).

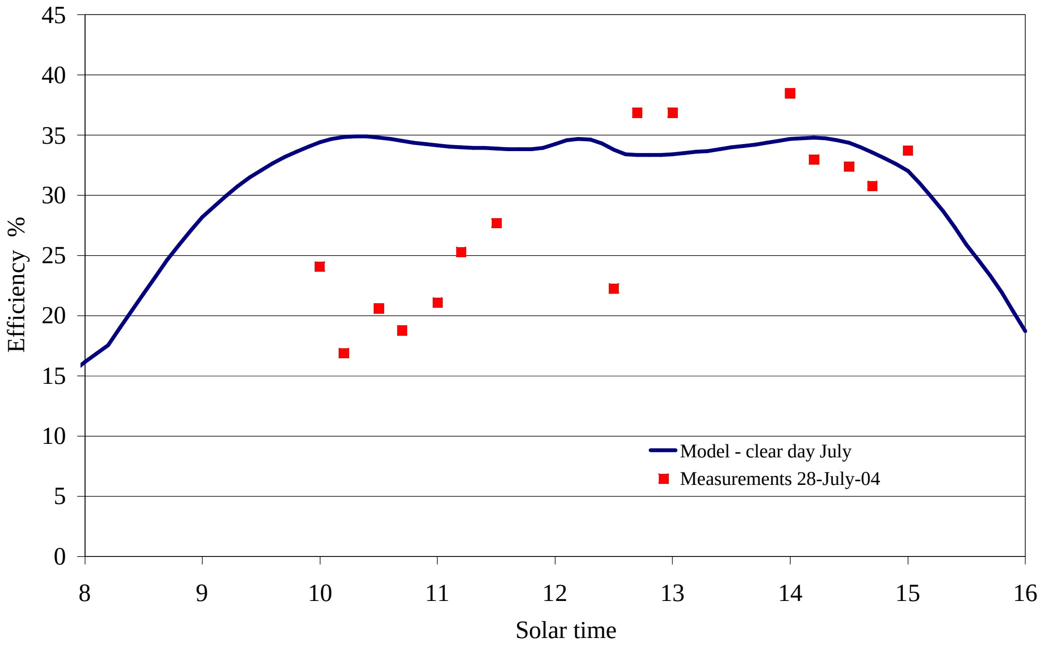

Fig 3. Measured and predicted performance of prototype array 28th July.

Testing commenced on the 28th at 10AM and the warm up curve of the array was recorded. Some cloud was reported but after midday and with warming up completed there was close agreement between measurements and the system model. Cloudless peak measurements between 12:45, and 15:00 were closely correlated to the performance predictions. Peak output measurements at 12:45, 13:00 and 14:00 were actually higher than predicted. Corrected thermal efficiency peaked at 14:00 with an (excellent) reading of 38.5%

Data collected from the testing and the subsequent corrected efficiency calculations are described below in Table 1

Table 1

Prototype low temperature performance 28 July 04

Time	Inlet temp °C	Outlet temp °C	Beam radiation W/m^2	Flow rate kg/min	Power kW	Efficiency	Unilluminated absorber m	Efficiency corrected
10:00	20	35	844	165	173	0.152	22.9	0.241
10:15	29	40	882	165	127	0.106	22.9	0.169
10:30	30	44	882	165	161	0.135	21.3	0.206
10:45	32	45	901	165	150	0.123	21.3	0.188
11:00	32	47	901	165	173	0.142	20.2	0.211
11:15	34	52	901	165	207	0.171	20.2	0.253
11:30	34	54	901	165	230	0.190	19.5	0.277
12:30	38	55	938	165	196	0.155	19.0	0.223
12:45	39	67	938	165	322	0.255	19.1	0.369
13:00	43	71	938	165	322	0.255	19.1	0.369
14:00	47	75	919	165	322	0.260	20.2	0.385
14:15	54	77	882	165	265	0.223	20.2	0.330
14:30	55	77	882	165	253	0.213	21.3	0.324
14:45	57	77	844	165	230	0.202	21.3	0.308
15:00	58	79	844	165	242	0.212	22.9	0.337

3.2. Steam Trials

Fig. 4. The array venting steam for the first time on August 19.

The first proving steam trial was held in August (Fig. 4) in clear still weather without a cover over the absorber. Steam production began at 9 AM and the design temperature of 285 °C was met and the design pressure of 69 bar was exceeded with a measured 80 bar (295°C at saturation inside the tubes at the outlet). The measured temperature figure is lower than that in the array receiver because of cooling through the vertical uninsulated pipes leading to the outlet monitoring point at ground level. The expanded steam temperature was measured to be 120°C, indicating that the absorber outlet steam dryness fraction was greater than 0.95 at 80 bar (Fig. 5). This range of operation is the best from the point of view of absorber pressure drop, tubing damage and unstable slugs of water. In general, operation was stable and steam at the design pressure was produced reliably on several days. Steam system operation will be investigated further under a recent grant from the NSW Sustainable Energy Research and Development Fund. The Direct Solar Steam (DISS) project at the Plataforma Solar de Almería (Zarza et al, 2004) uses a series of parabolic troughs approximately 500 metres long. Control of the once-through steam flow in the large diameter absorber tube used in the DISS project was found to be difficult to control, and recirculation and injected flow controls had to be added to the DISS system. Such approaches to system control do not appear to be necessary for the CLFR system, which is producing slightly wet steam over the day without any of the flow instabilities reported in the DISS project. This will have to be further confirmed under a wider range of operating conditions.

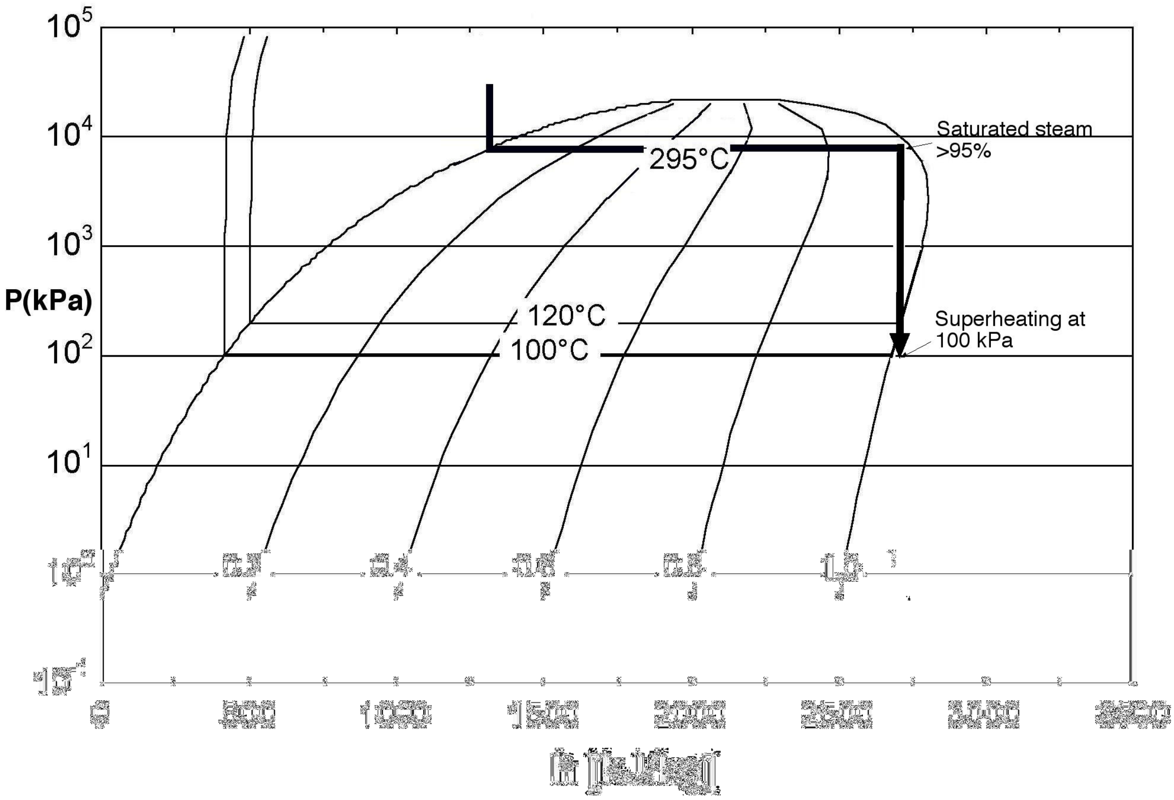

Fig. 5. Steam phase diagram showing that if steam were produced at 295°C and 80 bar inside the tubes, it is be superheated (dry) when released to atmosphere. The figures along the 10^0 line indicate steam dryness fraction. The steam dryness fraction is greater than 0.95 at the internal absorber outlet.

4. MODELLING ESTIMATIONS OF FUTURE PERFORMANCE

Table 2
Energy delivery per unit mirror area at 270°C

	Output MJ/m^2 North-south	Output MJ/m^2 East-west
JAN	439	366
FEB	310	258
MAR	278	232
APR	212	177
MAY	126	105
JUN	93	77
JUL	144	120
AUG	187	156
SEP	223	186
OCT	330	275
NOV	360	300
DEC	437	364
Annual	**3139**	**2618**

The modelling results have been confirmed by the initial experiments, and these bolster the predictions that are made for performance in a typical year. Table 2 shows predicted thermal output throughout the year in MJ/m^2/day for an east-west aligned array. Although performance is more extreme seasonally in the north-south aligned array, annual performance shows a 17% increase if the north-south orientation is chosen. It is therefore likely that the north-south orientation, which was used in Stage 1, will be maintained for subsequent stages.

5. SUMMARY AND DISCUSSION

Stage 1 of the CLFR Project has been successfully installed and optical measurements closely match modelling predictions for the time of year, indicating that a Stage 3 array peak thermal output of more than 100 MW (th) can be expected from 135,000 m^2 in mid-summer. The design internal absorber steam temperature of 285°C and 69 bar pressure were exceeded during winter conditions, and saturated steam generation at 80 bar with a dryness fractioin of 0.95 was achieved; this is in the range used by conventional boilers. Steam production appears quite trouble-free, a stark contrast to attempts to develop direct steam generation in parabolic trough collectors for the last two decades. SHP will perform further testing on the Stage 1 array during a variety of weather conditions in coming months.

CLFR technology is now close to commercial exploitation for the coal saver market as the array is performing as expected and has been constructed on budget. Future use in stand alone solar plants is also envisaged, using low temperature turbines.

REFERENCES

Buie D., Dey C. J. and Mills D. R. (2002) *Optical considerations in line focus Fresnel concentrators*, Proceedings of the 11th SolarPACES International Symposium on Solar Thermal Concentrating Technologies, 4-6.Sept. Zurich Switzerland, 2002.

Mills D R , Morrison G L, Le Lievre P (2004) Design of a 240 MW_e Solar Thermal Power Plant. Proc. Eurosun Conference, Freiburg, June 2004.

Mills D R and Morrison G L (2000), *Compact Linear Fresnel Reflector solar thermal powerplants*, Solar Energy, vol 68 (3), 3 March 2000, pp. 263-283 http://dx.doi.org/10.1016/S0038-092X(99)00068-7

Pye J D, Morrison G L and Behnia M (2003), *Transient modelling of cavity receiver heat transfer for the compact linear Fresnel reflector. Proceedings of ANZSES Solar 2003, Melbourne, pp 69-78*

Reynolds D., Jance M., Behnia M. and Morrison G.L. (2004), *An Experimental and Computational Study of the Heat Loss Characteristics of a Trapezoidal Cavity Absorber, Solar Energy V76, 229-234, 2004*

Reynolds D J, Behnia M and Morrison G L (2002), *A Hydrodynamic Model for a Line-Focus Direct Steam Generation Solar Collector, Proceedings of ANZSES Solar 2002, Newcastle, Australia*

Zarza E, Valenzuela L, León J, Hennecke K, Eck M, Weyers H-D, and Eickhoff M (2004), *Direct steam generation in parabolic troughs: Final results and conclusions of the DISS project, Energy, vol. 29 (5-6), April-May 2004, pp. 635-644, SolarPACES 2002, http://dx.doi.org/10.1016/S0360-5442(03)00172-5*