Modelling of a 400m^2 steam based Paraboloidal Dish concentrator for solar thermal power production

P.Siangsukone and K. Lovegrove
Centre for Sustainable Energy Systems
Australian National University
Canberra, ACT 0200
AUSTRALIA
E-mail: piya.siangsukone@anu.edu.au

Abstract

The Australian National University has a 400m^2 Paraboloidal dish solar concentrator system, informally named "the Big Dish" that produces superheated steam via a receiver mounted monotube boiler. The system, (shown in Figure 1) which is the worlds largest was constructed in 1994. This paper describes the results of the latest experimental tests plus associated system performance modelling. The system was modelled in the context of feasibility study and performance assessment for multiple dishes, central generation Rankine cycle power plants using the transient simulation package TRNSYS. The new custom components of the TRNSYS deck file constructed for this study are the Paraboloidal dish, the steam generating cavity receiver, steam line and steam engine. These component models are based on transient model using the energy balance equation and the empirical derived formulation. Validation test were performed by comparing with the latest experimental results measured with a 1-minute time step.

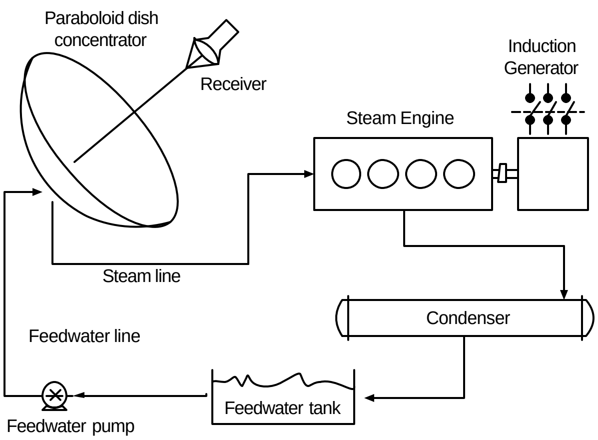
INTRODUCTION

Dish-based solar thermal systems have been advocated at the ANU since the 1970s. The early work lead to the construction of a 14 dish pilot facility (20m^2 dishes), which was built and tested in the 1980s to power a remote village (White Cliffs, New South Wales) (Kaneff, 1998). This was followed by the prototype 400m^2 dish "Big Dish" with a 50 kW$_e$ steam engine completed on the ANU campus in 1994.
Dish-based 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. Such a model is also needed to develop component designs that are adequately sized and to achieve an exergo-economic optimisation of the entire system. The feasibility of proposed solar thermal power plants can be assessed with such a system analysis and it also assists in analyzing a plants performance once operational (Kreetz, 2001).
Many computer software programs have been developed for modeling and simulation of solar energy systems. For this study TRNSYS15 with IISiBat3 was chosen as it offers many advantages; including the availability of a library of components common to different solar systems, the capability of interconnecting system components in any desired manner to accomplish a specified task and user friendly tools to facilitate the creation of custom components.
This paper presents an update of the work on modeling and simulation of the ANU 400m^2 Paraboloidal dish concentrator system with a direct steam generating cavity receiver. Additionally steam line and the steam engine are developed. The TRNSYS model predictions are compared with plant data measured with the ANU dish.

THE BIG DISH (SG3) SYSTEM

The SG3 (designated Solar Generating System 3) or informally named "the Big Dish" is 400m^2 dish system that employs 54 triangular mirror panels supported on a hexagonal aperture space frame structure, as shown in Figure 1. Altitude azimuth tracking is employed, with the horizontal axis near the base of the dish so that it can be parked in a horizontal position relatively close to the ground. This helps to reduce wind loads and so improve storm survivability. The SG3 dish has a cavity receiver based on a single helical winding of stainless steel tubing. This receiver serves as a “once through” boiler, which produces superheated steam at around 5MPa and 500^{o}?C. This steam is passed to the ground via a steam line and rotary joints for expansion in a grid-connected steam engine/ generator Unit (Kaneff, 1998).

The system converts the thermal energy in solar radiation to mechanical energy and then to electrical energy in much the same way that conventional power plants convert thermal energy from combustion of a fossil fuel to electricity. Although intended for operation in large arrays integrated with a steam turbine, the SG3 prototype is currently connected to a small reciprocating steam engine, which is capable of generating 45 kW_e and is connected to the local grid.



A simple schematic of the system is shown in Figure 2. The dish collector tracks the sun and concentrates the incident sunlight which is focused to the receiver. Meanwhile, the water is pumped from the feedwater tank via the water line which conveyed together with the steam line to the receiver. At the receiver, the water will be heated and vaporized to steam. The steam is sent via the steam line to the steam engine fitted with an alternator for producing electricity. After expansion, the steam is condensed in the condenser and sent back to the feedwater tank to complete the cycle. In the actual SG3 system, there are of course numerous other components, for example, bypass valve, rotary joints, cooling tower and controllers.

TRNSYS SIMULATION

TRNSYS is an acronym for “Transient System Simulation program” which has been under development at the University of Wisconsin-Madison since the 1970’s (Klein SA et al. 1996). TRNSYS is written in ANSII standard Fortran-77 and its component library includes many of the components commonly found in thermal energy systems. This includes a Solar Thermal Electric Component (STEC) library been created under the SolarPACES umbrella as well as components that are not ordinary considered part of a system. Such components are utility subroutines that use to handle the weather and insolation data and output simulation results.

TRNSYS relies on a modular structure and system concept, which system is defined as a set of component that interconnected to accomplish the specified task. And in each model the functional relationships between its input and output quantities are defined using algebraic and first-order differential equations. Thus, system performance simulation can be done by collectively simulating the performance of the interconnected component. TRNSYS 15 has been specially designed for incorporation with IISiBat in order to use for Microsoft Windows and as such can take advantage of the many Windows features. IISiBat is a general simulation environment program which has been adapted to house the TRNSYS simulation software. Many powerful tools and utility programs can be housed within the IISiBat shell. In this way, a complete simulation package, from simulation engine programs and graphical connection programs to plotting and spreadsheet software, can be incorporated into one environment program (CSTB, 1998). Once a system model has been established, running TRNSYS causes the program to step through all the system components evaluating output variables at each time step. Thus, weather data (solar radiation, ambient temperature etc.) and all time dependent variables are determined and calculated every time step through the simulation time period. For a true thermal transient model, the transient equations in the modelled components are solved using either TRNSYS analytical solution or numerical solver features.

SG3 TRNSYS SYSTEM AND ITS COMPONENT

The system discussed here is a simplified version of the actual SG 3 system since to describe all of the SG3 elements in a model would cause a loss of generality in the results and be too complex to set up. Therefore, the model is limited to the essential core elements as shown in figure 2. The components included in the model are a paraboloidal dish collector, steam generating receiver, the steam and water lines, the condenser, the feedwater tank, the feedwater pump and steam engine. This system includes four new TRNSYS custom components; dish collector, steam cavity receiver, steam line or feedwater line and steam engine, and the existing component in either TRNSYS standard and STEC library.

Paraboloidal dish collector

A complex ray trace model must be used to determine a detailed flux distribution on a solar concentrator's focal plane (Johnston, 1995).To avoid such computational complexity within TRNSYS source code, a simple user-supplied table was created from multiple runs using the ray-trace optical model. Hence, the dish collector can be simply modelled by linearly interpolating from the table for capture percentage by the receiver or receiver diameter values. And the dish power is calculated based on:

$$\dot{Q}_{dish} = I \cdot \rho_{dish} \cdot \left(A_{dish} - \pi \cdot R^2_{rec,aperture}\right) \quad (1)$$

where I is direct normal insolation and $?_{dish}$ is the average mirror reflectivity. The total dish mirror surface is A_{dish} and $R_{rec,aperture}$ is the receiver aperture radius. This component has originally been created by Kreetz (2001) and developed by the author (2003). It is assigned as type 251 which provides 2 mode of operation. The first mode of operation is used when the power capture percentage by the receiver is given whilst the second mode is employed if the receiver aperture diameter is known. Both of these 2 modes offer the output power from the dish and the power that captured by the receiver. In addition to this, interception loss and capture percentage are determined. The limitation of this component is that the component relies on the input table which depends on the dish focal length. In this study it is fixed to 13.1m of focal length as used for the SG3 dish collector. Therefore, if the other dish geometry of different focal length is modelled a new input table will be required. In mode 1, there is currently also an input table that was created for the ANU 20m^2 dish by Kreetz (2001).

Solar cavity receiver

A new component (designated as Type 256) has been developed for modeling a direct steam generating cavity receiver. The receiver is analyzed as a single constant diameter tube. The tube is divided up into 3 sections characterized by the phase of the water, i.e.; liquid, mixture, and vapour. The transient behaviour and phase change condition is taken into account in the model which is based on energy conservation (1st law). In the single phase regions (liquid or vapour), the mass is considered to be approximately constant for the duration of a time step and the transient term in the energy balance is linked to the rate of change of temperature:

$$\dot{Q}_{sol} - \dot{Q}_{loss} + \dot{m}_i(h_i - h_o) = (M_{rec}C_{rec} + M_{FL}\frac{\Delta U}{\Delta T})\frac{dT}{dt} \quad (2)$$

where $\dot{Q}_{sol}$ and $\dot{Q}_{loss}$ are the input power from solar insolation and heat loss and the subscripts rec and FL refers to receiver and fluid respectively. u, v, and h is the internal energy, specific volume and enthalpy of the working fluid and T is the temperature. The subscripts i and o refer to the inlet and outlet states of the receiver. M and V are mass and volume. In the two phase region, the receiver section is isothermal and the transient term in the energy balance is related to the rate of change of mass in the section, which is related to the rate of change of average specific volume. Equation 3 expresses this:

$$\dot{Q}_{sol} - \dot{Q}_{loss} + \dot{m}_i (h_i - h_o) = \left(M_{FL} \left(\frac{\Delta u}{\Delta v} \right) + (h_o - u) \left(\frac{V_{FL}}{v^2} \right) \right) \frac{dv}{dt} \qquad (3)$$

Thermal losses from the receiver include three contributions;

1. Radiative heat loss through the receiver aperture
2. Convective heat transfer to the ambient air through the aperture and to the pipe as internal convective heat loss
3. Conductive heat loss through the receiver insulation.

The heat loss is calculated based on equation 4 using user-supplied coefficients.

$$\dot{Q}_{loss} = e_{rec} s\, A_T (T_{rec}^{\;4} - T_a^{\;4}) + UA_T (T_{rec} - T_a) \tag{4}$$

where e_{rec} and A_T are the receiver surface emissivity and the heat loss area. U is the overall heat loss coefficient for convection and conduction that derived from experiment. Term T_{rec} and T_a refer to the average receiver segment temperature and the ambient temperature. Reflection losses are assumed to be negligible and interception losses are accounted for in the dish component. The pressure drop in the receiver is highly dependent and very complicated to model, thus, a simply solution is the use of the standard expression (Darcy-Weisbach equation) with the empirical derived factor (EMP).

$$\Delta P = fL \frac{r U_m^2}{4r} * EMP \tag{5}$$

where ΔP is the pressure drop through the receiver. L and r are the length of internal radius of the receiver tube, r is the fluid density and U_m the mean fluid velocity. The friction factor f is calculated from the formulation of Swamee and Jain (Potter & Wiggert 1991).

The receiver and outlet fluid temperature is determined by numerically solving equation 3 & 4 using the finite time integration method. The average receiver temperature is stored and recalculated in each time interval by using the time derivative of receiver temperature and the average receiver temperature at the previous time step. Consequently, this model requires an approximately 10-15 sec. time step to achieve an accuracy of result. It is assumed that the solar input is uniformly distributed along the boiling tube and there is no temperature gradient between receiver wall temperature and the fluid temperature as the tube is well insulated. If these assumptions are not valid then a receiver can be modelled with two or more type 256 components in series.

Steam line or feedwater line

The steam line is the energy transportation part of a steam based distributed dish solar thermal power system. It can be simply modelled by modifying the steam cavity receiver component with the conditions that there is no insolation power input and no radiation and convection heat losses. This component can be served for all states of water, thus the model can be used either as the steam line or the feedwater line. The steam line is designated as Type 257. Unlike the receiver component, as there is no radiation loss involved in the model, the transient energy balance equation in the model can be easily solved by the TRNSYS analytical solution.

Steam engine

Steam engine model is assigned as type 259. It provides the electricity output based on the experimental derived formula from Bannister, (1991) described in equation 6.

$$P_{1:r} = -1.6N + h_{cyl\,1:r} \dot{Q}_{th} \tag{6}$$

where P is the engine power output and N is the number of cylinder. 1:r refers to expansion ratio engine which r is one of 10.1, 13.0, or 15.8. $h_{cyl\,1:r}$ is the coefficient of the thermal input which depends on the inlet steam temperature and condenser pressure as shown in equation 7.

$$h_{cyl\,1:r} = x_1 + x_2 T + x_3 T^2 + x_4 P_{cond} \tag{7}$$

where x_1,x_2,x_3, and x_4 are coefficient factors that depend only on expansion ratio. Thus, by use of Bannister expression, there is no need to model the detailed engine processes for a power output. However, to determine the back pressure and the outlet steam properties the intake and expansion process need to be modelled. The intake process is thermodynamically modelled based on the specific volume of steam entering the engine and its inlet temperature whereas the expansion process is modelled based on isentropic assumption.

RESULTS AND DISCUSSIONS

To validate the model, a comparison between the actual measured data and the model predictions has been made. Comparison with experimental data obtained on two representative days in September 1995 and January 2003 is presented here. The insolation data was recorded based on measurements from a pyrheliometer installed on the dish and the fluid mass flow rate is varied during the operation by the controller system. The experimental weather data file contains measurements of insolation, feedwater flow, system temperatures and various other variables measured at 1 minute intervals. Figure 3 and 4 show the insolation condition and the mass flowrate at the SG3 site on September 6, 1995 and January 9, 2003.

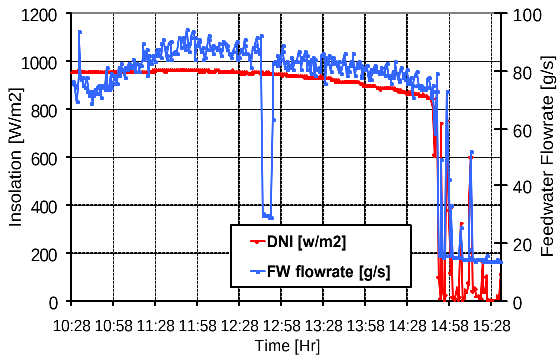


Figure 3: Insolation data on 6 Sep. 1995

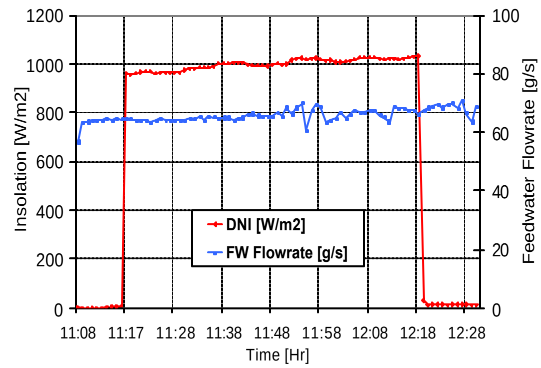


Figure 4: Insolation data on 9 Jan.2003

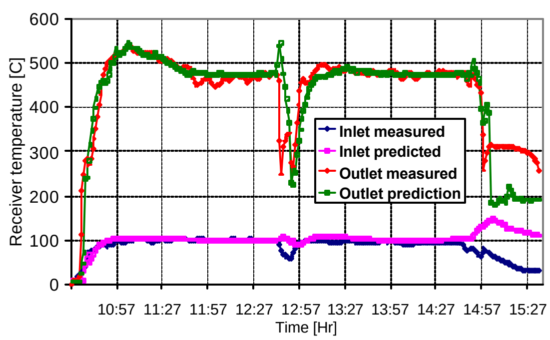


Figure 5: Measured and predicted receiver temperature on 6 Sep 1995

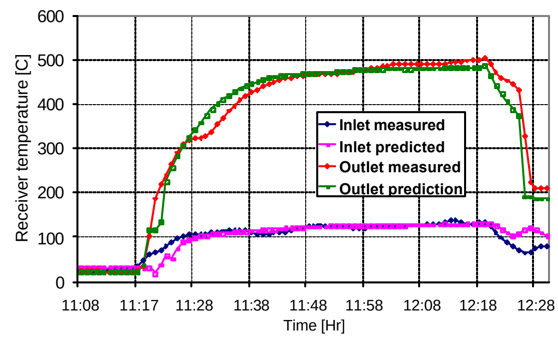


Figure 6: Measured and predicted receiver temperature on 9 Jan 2003

Figure 5 and 6 demonstrate the good agreement between the measured and predicted of inlet and outlet steam temperature from the receiver for these days. On 6 September 1995, the gap in the middle of the day is due to the dish being taken off the sun for a short period. The convection and conduction losses in the model have been adjusted to achieve agreement on the steady state energy balance. Figure 7 shows a comparison of receiver inlet and outlet pressure between the model and the actual measured data. The inlet receiver temperature and pressure are modeled using feedwater component (type 257) whereas the outlet condition is predicted from the receiver component. It should be noted that the receiver model used the actual measured inlet temperature data instead of the prediction from the feedwater model. Figure 8 and 9 show the comparison of exit temperatures from the steam line. The comparison shows the promising result of the steam line model. Figure 10 and 11 illustrate the power output results from steam engine model. The predicted are generally match the actual measured data excluding in some condition where the complicated bypass condition is not reached by the model.

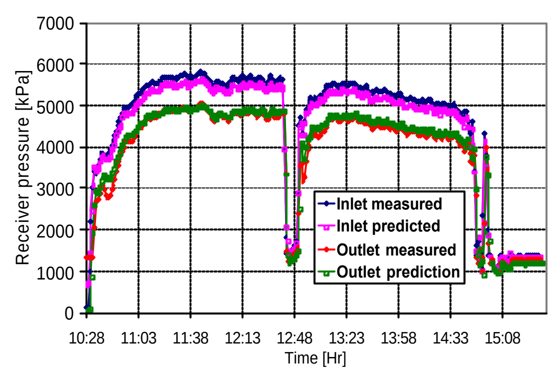


Figure 7: Measured and predicted receiver pressure on 6 Sep 1995

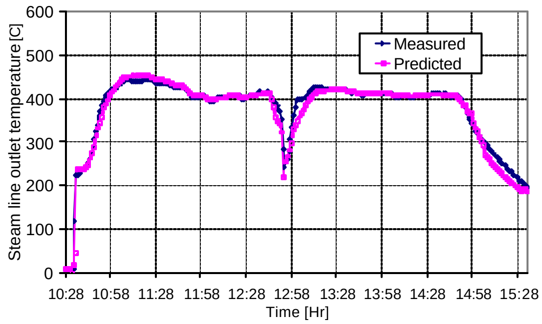


Figure 8: Measured and predicted steam line temperature on 6 Sep 1995

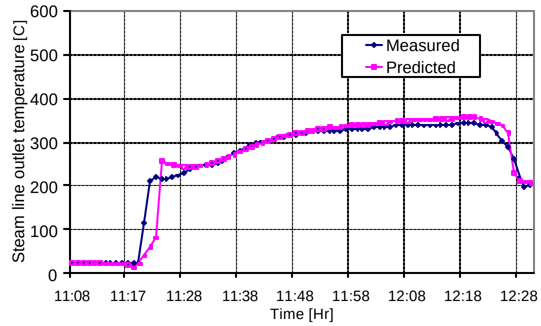


Figure 9: Measured and predicted steam line temperature on 9 Jan 2003

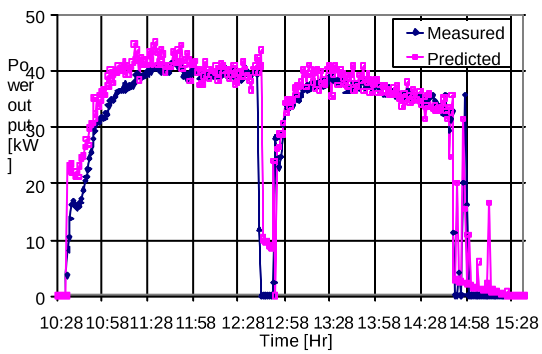


Figure 10: Measured and predicted power output on 6 Sep 1995

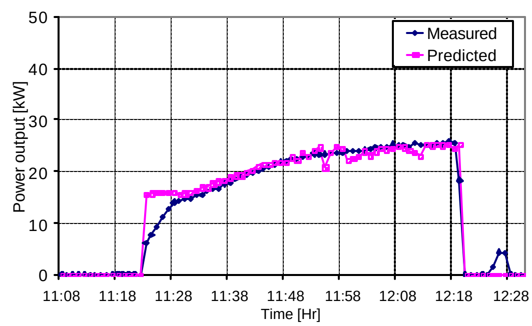


Figure 11: Measured and predicted power output on 9 Jan 2003

CONCLUSION

These preliminarily results show that the newly built TRNSYS components for Dish, Steam Cavity Receiver and Steam Line, work reliably in a system simulation. More investigation is required for model parametric study. When this has been done, the system model will also be extended to predict the optimum system operation. Moreover, the annual performance of multiple dishes Rankine cycle solar thermal power systems will be assessed. This will be a valuable tool in the development of designs for solar thermal power production systems.

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