Modelling of a steam based Paraboloidal Dish concentrator using the computer source code TRNSYS

Siangsukone P. and Lovegrove K.,
Centre for Sustainable Energy Systems
Australian National University
Canberra, ACT 0200
AUSTRALIA
Telephone: +61 02 6125 3338
Facsimile: +61 02 6125 0506
E-mail: Piya.Siangsukone@anu.edu.au

Abstract

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. This paper deals with the modeling and simulation of a Paraboloidal dish concentrator system with a direct steam generating cavity receiver. The Dish concentrator system consists of a Paraboloidal dish with cavity receiver and a steam line and is modelled using the TRNSYS simulation package. The main component of the TRNSYS deck file constructed for this study is the solar cavity receiver. This component models the energy balance in the receiver and takes into account the thermal mass of the steel tubing and the phase change of the water. A simpler steam line component has also been developed. The SG3 400m^2 dish system with steam receiver at the ANU has been chosen as a reference model for this study. Validation test were performed by comparing with experimental results measured with a 1-minute time step.

1 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 work on modelling and simulation of the ANU 400m^2 Paraboloidal dish concentrator system with a direct steam generating cavity receiver and the steam line. The TRNSYS model predictions are compared with plant data measured with the ANU dish.

2 SYSTEM DESCRIPTION

The SG3 400m^2 dish system 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 resistance 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).

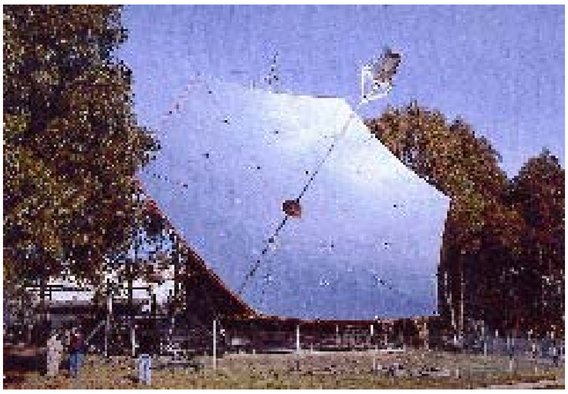

Figure 1: ANU's 400m^2 Paraboloidal Dish

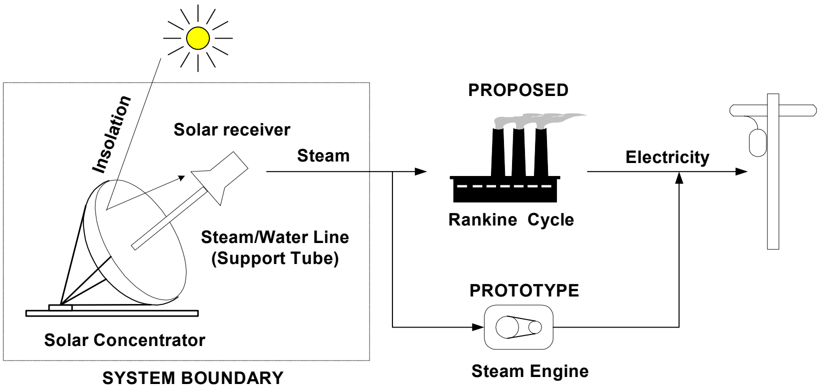

Figure 2: DSG Dish Rankine cycle Solar Thermal Plant

The SG3 Dish 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 as indicated in Figure 2. 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 is shown in Figure 3. Water is pumped from the feedwater tank to the receiver where it is 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 and controllers.

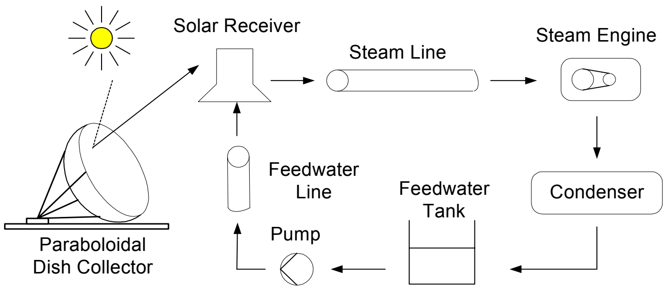

Figure 3: Simple Schematic of SG3 Parabolidal Dish system

3 SYSTEM SIMULATION

The SG3 system has been modeled using the TRNSYS program. TRNSYS, is an acronym for "Transient System Simulation program". It is a quasi-steady simulation model, which has been under development at the University of Wisconsin-Madison since the 1970's (Klein SA et al. 1996). With a program such as TRNSYS, a system can be simulated by making a set of software components which are interconnected in the same manner as the physical components of the system. TRNSYS 15 has been specially designed for incorporation with windows based interface, IISiBat. IISiBat is, an acronym for a French phrase that can be roughly translated as "Intelligent Interface for the Simulation of Buildings". It is a general simulation environment program which developed by the French Scientific Center for Building Physics. There are existing libraries of components which can be configured by the user by setting the values of their various parameters and linked together in the IISiBAT environment. Users also have the option of writing new components using Fortran source code. TRNSYS15 and its user interface IISiBat3 was chosen for this study as it offers many advantages and in particular a library of Solar Thermal Electric Components (STEC library) has been established and is being added to under the umbrella of the IEA SolPACES program (Pitz-Paal, 1998).

When a system model has been established, running TRNSYS causes the program to step the system through the simulation period by calculating a self consistent set of variable values at each time step. For a solar system, insolation and other time dependant empirical data such as mass flow, is provided as a table of values against time and these are used as inputs to the appropriate components. For a true thermal transient model, temperatures from a time step must be stored for use in calculating the temperatures at the next step

3.1 System Components

In this study, three new components have been developed. These are; paraboloidal dish, steam generating cavity receiver and steam line.

3.1.1 Paraboloidal Dish Collector

A component that predicts the receiver aperture diameter and output power from a 2 axis sun-tracking dish collector, has been written previously by Kreetz (2001). Kreetz used the component in modeling a thermochemical energy storage system, however it is directly applicable to steam based energy conversion as well. In the STEC library, it has been designated as "Type 251". This component has dish collector area, rim angle, surface slope error, and mirror reflectivity and percent capture by the receiver specified as parameters. The direct beam insolation is an input and the outputs are the receiver aperture size needed to achieve the percentage capture (this is fixed by the parameter values) and the power delivered to the receiver (which varies with the dish parameters and the insolation level). The component works simply by linearly interpolating from a look up table of values for capture percentage as a function of rim angle, dish collector area, surface slope error and receiver aperture. The table was derived from multiple runs using the ray-trace optical model developed by Johnston (1998). In fact the component contains tables for either smooth dishes or dishes with flat facetted mirror tiles.

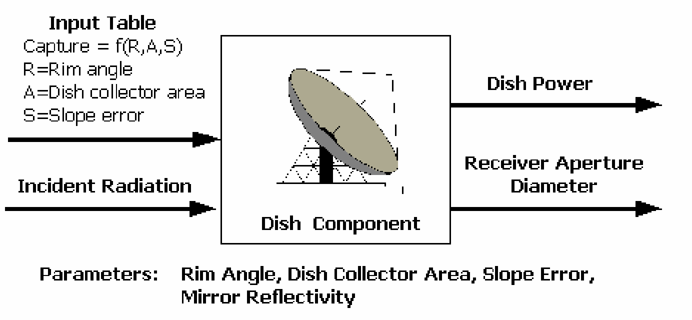

Figure 4: Steady State Dish Model with all Parameter

3.1.2 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, ie; liquid, mixture, and vapor. The transient behavior 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:

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

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 using equation 4 using user-supplied coefficients.

$$\dot{Q}_{loss} = \sigma A_T \left(T_{rec}^{\ 4} - T_a^{\ 4}\right) + h_{cv} A_T \left(T_{rec} - T_a\right) + \frac{\left(T_{rec} - T_a\right)}{R_{tot}} \qquad (4)$$

where A_T is the surface area of tube receiver, T_{rec} is the receiver temperature and Ta is the ambient temperature, R_{tot} is the thermal resistance of receiver for losses through its outer casing and h_{cv} defines the convective heat transfer coefficient, which assumes to be constant for all regions in receiver. Reflection losses are assumed to be negligible and interception losses are accounted for in the dish component. The receiver and outlet fluid temperature is determined by numerically solving equation 2 & 3 using the finite time integration method.. T_{rec} is stored and recalculated in each time interval by using the time derivative of receiver temperature and T_{rec} 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 boiler tube and the pressure remains constant during the process. If these assumptions are not valid then a receiver can be modeled with two or more type 256 components in series.

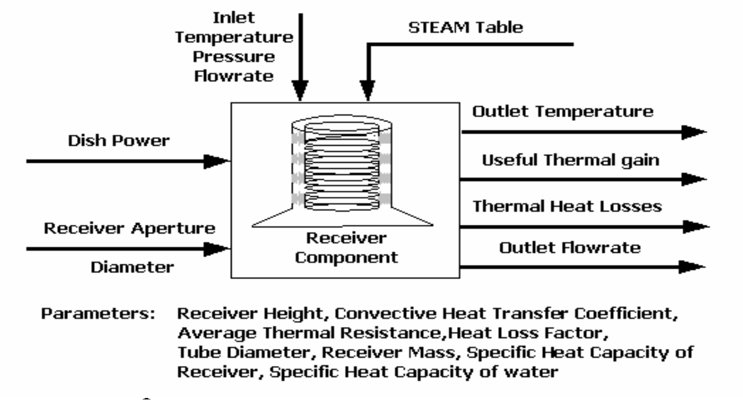

Figure 5: Transient Steam Cavity Receiver Model.

3.1.3 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 serve for all states of water, thus the model can be used either as the steam line or the feedwater line. The single phase governing equations- becomes:

$$\dot{m}_i C_{FL}(T_i - T_o) - \frac{T - T_a}{R_{tot}} = \left(M_p C_p + M_{FL} C_{FL}\right)\frac{dT}{dt} \qquad (5)$$

and the two phase case is:

$$\dot{m}_i (h_i - h_o) - \frac{T - T_a}{R_{tot}} = \left(M_{FL}\left(\frac{\Delta u}{\Delta v}\right) + (h_o - u)\left(\frac{V_{FL}}{v^2}\right)\right)\frac{dv}{dt} \qquad (6)$$

where T and h refer to the temperature and enthalpy, the subscripts p and FL refer to pipe and fluid respectively. C refers to the specific heat capacity and R_{tot} is the overall thermal resistance of the pipe. The steam line is designated as Type 257. Unlike the receiver component, equation 5 can be easily solved by the TRNSYS Differential Equation solver since there is no T^4 term. However Equation. 6 is numerically solved the same as in the receiver component due to the relationship between enthalpy and temperature being more complex.

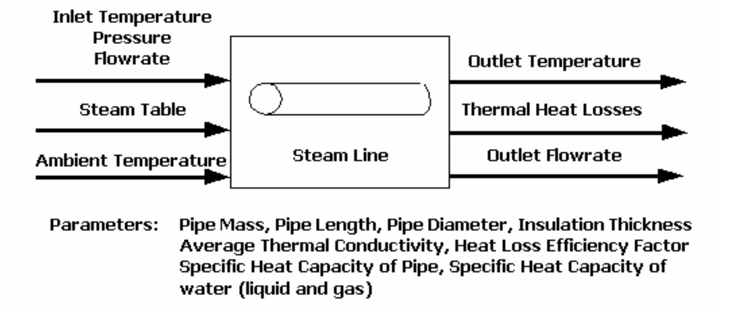

Figure 6: Transient Steam Line Model with all Parameter

3.2 TRNSYS Model

To implement TRNSYS to model the SG3 400m^2 dish with steam generating receiver and steam line, additional components are required; Type 9 data reader, Type 16 radiation processor, Type 3 pump, Type 25 printer and Type 65 online plotter. Once all components have been identified, it is necessary to construct an information flow diagram for the system. The purpose of the information flow diagram is to facilitate identification of the components and the flow of information between them. Each component is represented as a box, which requires a number of constant Parameters and time dependent Input and produces time dependent Outputs. An information flow shows the manner in which all components are interconnected. A given Output may be used as an Input to any number of other components (Beckman et al., 1994, Klein, 1976a, Klein, 1976b). A simplified information flow diagram for SG 3 dish receiver system is shown in Figure 7. And the example of TRNSYS model (in IISiBat 3 window) of this system is shown in figure 8.

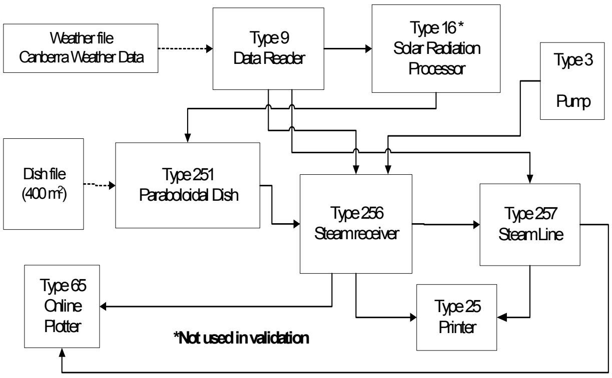

Figure 7: Information Flow Diagram of SG3 Paraboloidal Dish Concentrator System

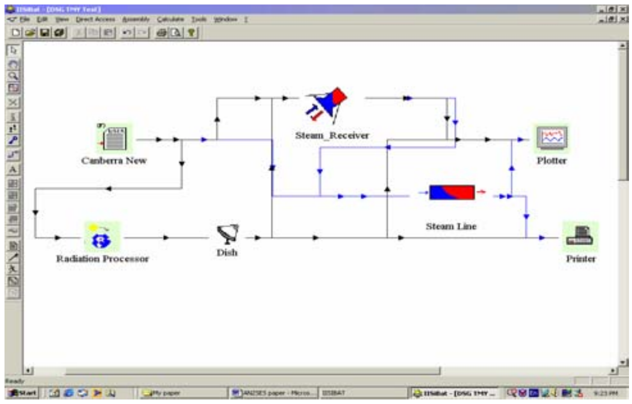

Figure 8: SG3 Dish Receiver TRNSYS Model

3.3 Results

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 is presented here. The insolation data was recorded based on measurements from a pyrheliometer installed on the dish and the fluid mass flowrate 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 9 and 10 show the insolation condition and the mass flowrate at the SG3 site on September 6, 1995 and October 24, 1995.

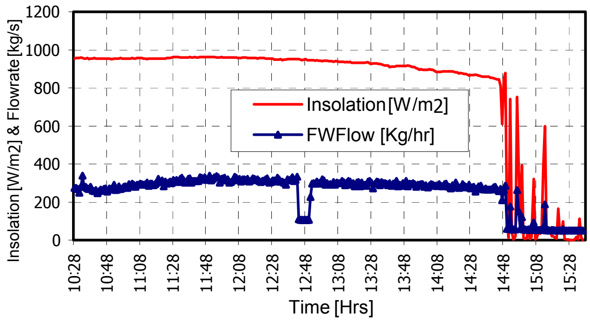

Figure 9: Insolation Data on 6/09/95

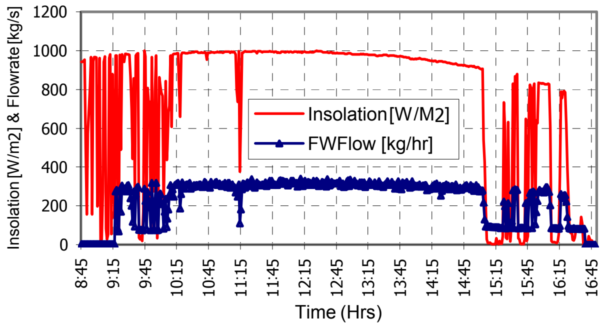

Figure 10: Insolation Data on 24/09/95

Figure 11 and 12 demonstrates the good agreement between the measured and predicted outlet steam temperature from the receiver for these days.

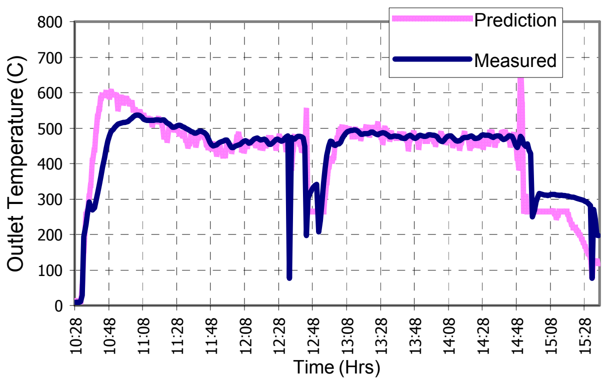

Figure 11: Measured and Predicted Receiver Outlet Temperature on 6/09/95

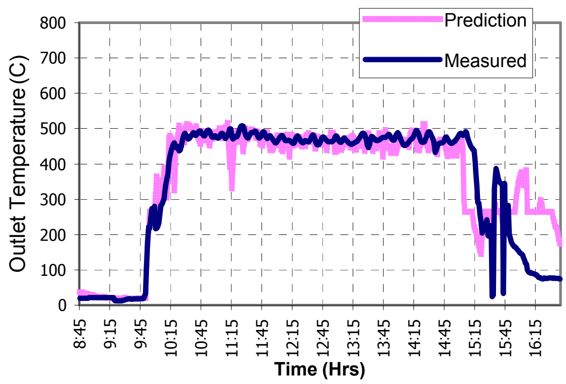

Figure 12: Measured and Predicted Receiver Outlet Temperature on 24/10/95

The apparent overestimation of the exit temperature by the model at the start up time in figure 7 is explained by the dish being partially shaded by trees in the morning for about an hour. 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. The mass incorporated in the model is based on a calculation of tube mass. The more "noisy" response of modeled temperature fluctuations compared to the measurements suggest that this may provide an underestimate of the effective "lumped thermal capacitance" of the receiver. It may also explain the temporal mismatch at the late afternoon seen in figure 8.

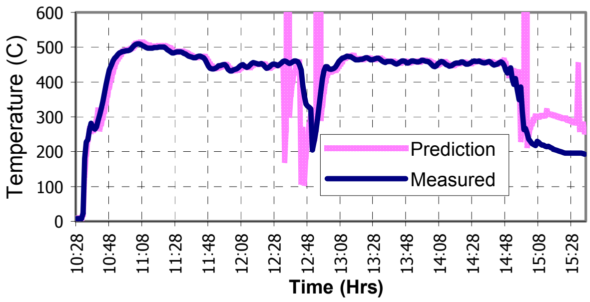

Figure 13: Measured and Predicted Steam Line Outlet Temperature on 6/09/95

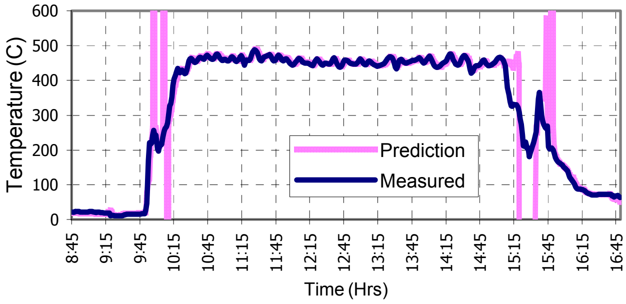

Figure 14: Measured and Predicted Steam Line Outlet Temperature on 24/10/95

Figures 13 and 14 show the comparison of exit temperatures from the steamline. In this case the steamline model used the actual measured inlet temperature data instead of the prediction from the receiver model. The model shows the good agreement overall but some unexplained excessive transient behaviour in the regions of major temperature changes that need further investigation.

4 CONCLUSIONS

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 to determine the precise method for allocating thermal mass and checking computational stability under major input transients. When this has been done, an extensive parametric study of SG3 predicted performance will be carried out.

Other SG 3 components, such as rotary joint, condenser and heat exchanger will be developed in order to complete the full operation of SG3 model.

The system model will also be extended to predict the annual performance of multiple dish Rankine cycle solar thermal power systems. This will be a valuable tool in the development of designs for demonstration systems.

5 REFERENCES

Bannister, P. (1991). *An Experimental and Analytical Assessment of a steam rankine solar thermal system*, Ph.D. Thesis, Energy Research Center, The ANU, Australia

Beckman W.A., Broman L., Fiksel A., Klein S.A., Lindberg E., Schuler M. and Thornton J. (1994). *"Trnsys - the most complete solar energy system modeling and simulation software",* Renewable Energy, vol. 5, pp. 486-488

Johnston, G. (1998) *Focal region modeling and characterization of paraboloidal dish solar concentrators,* Faculty of Engineering and IT, The ANU, Australia

Kalogirou S.A. (2001) "*Use of TRNSYS for modeling and simulation of a hybrid pv-thermal solar system for Cyprus*" Renewable Energy 2001;23:247-260

Kaneff, S. (1998). *Final Report on the Single, Large Dish Solar Thermal System for the New South Wales Department of Energy-1988-1998*, Energy Research Center, ANUTECH Pty Ltd., Australia

Klein SA et al. (1996) *TRNSYS 14.2*, *A Transient Simulation and Programming*, Madison (WI): Solar Energy Laboratory, University of Wisconsin.

Kreetz, H. (2001) *Heat recovery in a solar thermal Power system*, Faculty of Engineering and IT, The ANU, Australia

Pitz-Paal R. and Jones S. (1998). *A TRNSYS model library for solar thermal electric components (STEC)* Technical Report; DLR Koeln: Koeln, Germany.

Pitz-Paal R. and Jones S. (1999). *A model library of solar thermal electric components for the computer code TRNSYS* Journal de Physique IV, vol. 9, pp. 593-598.

Solar Energy Laboratory, University of Wisconsin-Madison (2000a). *TRNSYS-A transient simulation program Version 15 Volume I* Madison, WI, USA, 2000a.

Solar Energy Laboratory, University of Wisconsin-Madison (2000b). *TRNSYS-A transient simulation program Version 15 Volume III-Introduction to TRNSYS with IISibat* Madison, WI, USA, 2000b.