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REVIEW ARTICLE

Simulation of Solar Thermal Central Receiver Power Plants: A Review

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Abstract

Large space is required for central receiver solar thermal power plants and also its components are costly therefore experimental work for such power plant is costly and time consuming. This shows the necessity to master user friendly modeling and simulation tools for designing and optimizing the solar power plant. A number of software and tools are developed and are still available for the modeling and simulation of central receiver solar thermal power plants. Some of the software help in analyzing the performance of individual components of the power plant whereas some software help to analyze and predict the performance of the entire plant. None of such software can be considered as standard tool for research. This paper presents a review and evaluation of software used for central receiver solar thermal power plants. Existing software are screened to determine which one should be used depending on the objectives of the simulation and expected results. A summary of all the software is presented with recommendations regarding its use.

Introduction

Concentrated solar power is considered the most large scale power renewable generation. India has good solar insolation in almost all parts of the country. Its equivalent energy potential is about 6,000 million GWh of energy per year. Solar energy can be utilized to convert into electrical energy with the help of solar thermal power plants. Of all the technologies being developed for solar thermal power generation, plants based on Solar Thermal Central Receiver System are able to work at the highest temperatures and to achieve higher efficiencies in electricity production

In central receiver power plants shown in Fig1, solar radiation reflected from array of large mirrors called heliostats is concentrated on a receiver situated at the top of a supporting tower. Concentrated radiation is absorbed by the fluid inside the receiver. The receiver is used to heat water, liquid metal or molten salt and this fluid is passed through a heat exchanger in which steam for the power cycle is generated. Along with heliostats and receiver, storage tank, heat exchanger, blowers, valve and power block consisting of turbine, generator are the components of Central receiver solar power plant. Large space is required for installation of such plants. Experimentation is also costly and time consuming. Therefore to reduce the effort and time, modeling and simulation of plants is carried by many researchers. Models are developed for the heliostats, receiver, energy storage tank, heat exchanger and turbine and integrated them for the analysis of the plant.

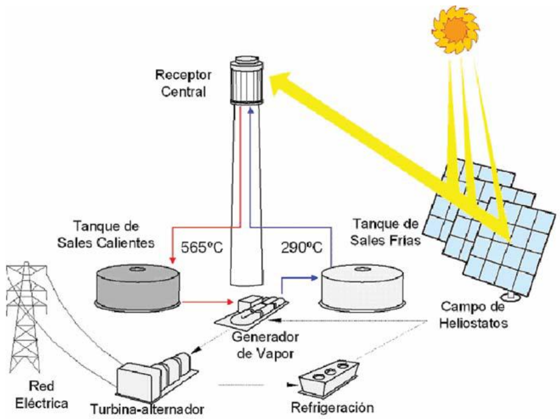

Fig1. Central Receiver Solar Power Plant with two tank storage system

Existing Central Receiver Solar Thermal Power Plants

Nine central receiver solar thermal power plants are built as listed in Table1. All these plants were conceived for experimental purposes and none including Solar One and Solar Two may be considered as prototype of a commercial size plant. All these projects were designed to investigate electricity production, which is only one of the possible utilizations of the central receiver technology. Four new central receiver plants are under construction in China and Spain.

Table 1. Central Receiver Power plants in the World.

S.No.	Plant	Location	Capacity (in MW)
1	SSPS-CRS (1981-1985)	Spain	0.5
2	Eurelios (1980-1984)	Italy	1
3	CESA-I (1983-1984)	Spain	1
4	Sunshine (1981-1984)	Japan	1
5	Themis (1983-1986)	France	2
6	CES-5 (1985-1989)	USSR	5
7	Solar-One (1982-1988)	USA	10
8	PHOEBUS (1992-1995)	Spain	2.5
9	Solar Two (1995-1999)	USA	10
10	DAHAN (under construction)	China	1
12	PS10	Spain	10
13	Gema Solar	Spain	19.9

Simulation

From literature review it is found that not much detailed published information is available on the simulation of central receiver solar thermal power plant as an integrated plant in open literature. None of the software available for simulation of solar power plant can be considered as a standard software as the features and needs of solar power plants vary from plant to plant and a lot of work is needed in these software to make them suitable according to the need of specified plant. In this paper, existing software for simulation will be discussed along with their objective and expected results. These simulation software play important roles in performance calculation of one of the components of solar power plant or integration of the components to form whole plant model. These can be used to design experiments in which either direct or indirect measurements may be taken and from which receiver performance can be calculated, to supplement measurements whenever measurements are difficult to make (e.g. convection heat losses) and to provide estimates of values for comparison with measurements.

Mathematical models of the real processes of solar central receiver power plant cannot take all aspects into consideration; therefore simplifying assumptions are required for modeling. Thus models are approximations of reality. First step in modeling of central receiver power plant is the modeling of basic components of central receiver power plant. In second step, the process variables of the plant are indentified. The third step is the analysis of the way in which the variables are dynamically related. The energy balance model of the solar central receiver power plant with the main components and related process variables is shown in Fig2.

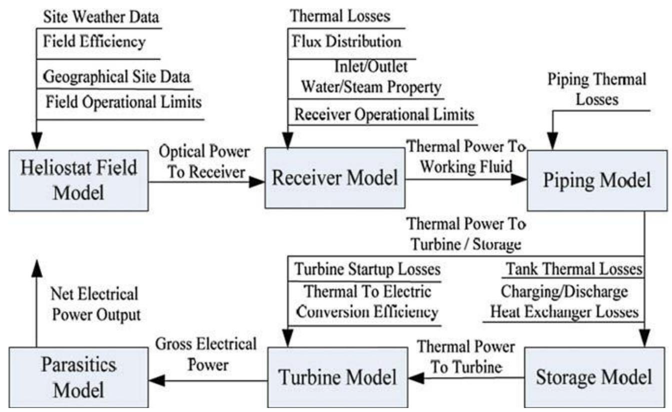

Fig3. Energy Balance Model Of Central Receiver Solar Thermal Power Plant

Incident Flux Estimation and Performance of Heliostat Field

MIRVAL

In 1979, Leary and Hankins developed software called MIRVAL which simulates the individual heliostats and a portion of the receiver as it calculates the optical performance of well defined solar thermal central receiver power plant. It evaluated and compared the fixed heliostats, field and receiver designs. The effects of shadowing, blocking, heliostat tracking and random errors in tracking, confirmation of the reflective surface, insolation, angular distribution of incoming solar rays to account for limb darkening and scattering, attenuation between the heliostats and the receiver, reflectivity of mirror surface and aiming strategy. Three receiver types – external cylinder, cylindrical cavity with a downward facing aperture and north facing cavity and four heliostat types can be analysed with this software. Input and computer time requirements limit its utility in receiver evaluation. The complex geometry of CETHEL heliostats of the Themis field could not be modeled by MIRVAL.

HELIOS

HELIOS determines the solar flux density by using cone optics. It analyses the flux density arising from fields of 1 to 559 individual heliostats or 559 cells containing multiple heliostats. It is used to study the effect of declination of the sun, earth orbit eccentricity, molecular and aerosol scattering, atmospheric refraction, angular distribution of incoming solar rays, reflectivity, shapes of focused facets and error distributions in the surface curvature, aiming, facet orientation and shadowing and blocking. HELIOS is used when a detailed description of the heliostat is available and an extremely accurate evaluation of flux density is needed.

NS Code

Optical performance and optimization of heliostat fields of a number of central receiver systems including Solar one and Solar Two were performed by NS code developed by UNIVERSITY OF Houston (Lipps and Vant-Hull) in 1978. It was used for evaluating the optical performance of a specified central receiver field to produce flux maps for external surround, cavity and flat plate types of receivers. The solar field is divided into cells corresponding to regions with uniform heliostat density or fixed number of heliostats or single heliostat and performance is calculated for a representative heliostat in each cell. The flux map algorithm is based on a two dimensional Hermite expansion method. Special timimg sequences provide sunrise startup data and cloud passage data. In addition, drift studies provide for multiple flux maps with the heliostats either fixed (sun drift) or skewed on either axis. A typical flux calculation takes less than 30 seconds on a VAX 780. In 1984 NS Code was modified by Falcone and computing time was saved. This software was further modified by Pitman and Vant Hull in 1989 during Solar Two design and operation. An allowable flux constraint was used to optimize the new heliostat layout. A C++ version of this software incorporating the structure and imaging characteristics helped to compute in real time, aiming strategies to control solar flux density on a receiver

HFLCAL

Kiera developed HFLCAL (Heliostat field layout calculations) software in 1986 for GAST hybrid concept and then applied to other concepts like Phoebus. It uses a simplified optical model with flux distribution reflected by each heliostat approached by a circular Gaussian distribution obtained by convolution of three distributions- one accounting for the size and luminance of the sun, second for heliostat error and third one for tracking errors. HFLCAL was used for SOLGATE project. It calculates the annual production of a central receiver plant depending on its specific configuration of heliostatic field/tower/receiver/cycle. The system is optimized to maximize electricity production per heliostat or minimize the cost of produced electricity. It is still used by DLR researchers for central receiver modeling.

Receiver Performance

CAVITY

CAVITY solves the energy balance equation for a solar cavity receiver (Winter, C. J., 1991). This software is designed to couple the solution of radiation exchange in cavity type receivers with the conduction convection exchange to the working fluid. Radiation losses are included in the analysis and an estimate is made of convective losses. It is used to model any working fluid for which property data exists. With the known values of initial surface temperatures, the radiative exchange matrix and the incident solar flux for each surface, the information about all surface temperatures and flux level for all elements, flow rates, pressure drop, incident energy, absorbed energy, convective energy losses, radiative energy losses and average surface temperature. This software is no longer maintained.

DRAC

Both transient and steady state thermohydraulic phenomena in solar receiver tubes can be modeled with the help of software called DRAC developed by Sandia National Laboratories (Winter) in 1983. If time dependent incident heat flux profiles and flow rate changes are specified, DRAC calculates the resulting transient excursions in tube wall temperature and fluid properties. Any receiver fluid can be modeled for which thermodynamic data exists.

RADSOLVER

To calculate the radiation energy transport in arbitrarily shaped solar cavity receivers, a software called RADSOLVER was developed by Sandia National Laboratories (Abrams M, 1981). In contrast to the common assumption of gray surfaces used in the modeling of radiation transport, RADSOLVER accounts for the wavelength dependence of emission and reflection using an arbitrary number of wavelength bands. The phenomena included in RADSOLVER are thermal emission, reflection and absorption of thermally emitted solar energies and multiple reflections of both type of radiant energy among the zones of the cavity. It calculates radiation heat transfer among cavity zones and to working fluids, irradiation and temperatures on adiabatic zone surfaces. Convection of air within the cavity is neglected. This software has not been used in many years.

Entire Plant Performance (Including Heliostat, Receiver, Heat Transfer Fluid, Storage)

DELSOL

DELSOL developed by Kristler in 1986 is a performance and design optimization software developed by using FORTRAN 77. It uses an analytic Hermite polynomial expansion/convolution of moments method for predicting images from heliostats. Time varying effects of insolation, cosine, shadowing and blocking and spillage along with atmospheric attenuation, mirror reflectivity and receiver absorptivity. Although receiver radiation and convection losses are also calculated, the detail is probably insufficient for use in receiver evaluation, thus only flux density calculation capabilities are used for receiver analysis. Receiver dimensions and tower height can also be evaluated with DELSOL. DELSOL does the calculations much faster than MIRVAL or HELIOS. Sandia National Laboratories, several other research organizations and industries still use DELSOL.

SOLERGY

The pilot plant Solar One was a result of the design proposals compared by solar central receiver annual energy simulation software STEAC. However the actual energy produced by the plant was different than the results given by STEAC. Parasitic electrical power consumption over the entire day was not taken into account in STEAC, due to which the results differed from actual values. For more realistic prediction capability, STEAC was rewritten, improving its capabilities, taking into account parasitic electrical power consumption and was renamed SOLERGY in 1987. It simulates the operation and annual power output of a solar central receiver power plant using an actual or simulated weather data recorded at time intervals as short as 7.5 minutes. The relatively short time intervals are required to model plant start up and the effects of cloud transients. It calculates the net electrical energy output including parasitic power requirements over 24 hrs a day. It has subroutine for each major plant system, i.e heliostat field, receiver, thermal energy storage and turbine. Annual plant performance is found by adding the performance at every considered time step. SOLERGY models only single phase fluids (e.g. molten salt and liquid sodium). Water/steam systems could also be modeled with some modifications and assumptions. Storage model supports start up delays and allows the energy in storage to fall below zero. Turbine model supported delays for turbine roll, generator synchronization and ramp to full load. Off design operation of the turbine could also be modeled with SOLERGY. Power flow calculations were made for each time step which could be as small as 0.125 hr. At earlier stage, the energy collected by the receiver subsystem was sent to thermal storage but later it was modified so that the collected energy could bypass storage for analysis. This software is developed in FORTRAN 77 and input is entered via user specified text files.

Solar Advisor Model

Solar Advisor Model (SAM) – establish connection between market requirement and research and development effort and how research and development efforts improvements contribute to overall system cost and performance. This software can predict the performance and economics of parabolic trough systems. Central receiver solar thermal power plants simulation is under development along with DELSOL and TRNSYS. The development work is taken by University of Wisconsin.

TRNSYS

TRaNsient System Simulation (TRNSYS) software is based on graphical user interface that allows drag and drop construction of the models. Different transient systems can be modeled by using these modular components. Each component represents a physical process or feature in the system and components can be developed as needed to a system model. Components include solar thermal collectors, heat exchangers, thermal storage tanks, hydraulic, controllers etc. Specific processes can be modeled for subcomponents of the total system and total system performance analyses can also be performed. It was developed by University of Wisconsin.

TRNSYS has been used to do the simulation of CESA –I facility – a central receiver solar thermal power plant located in Spain. The main phenomena of plant are related to thermofluids, therefore Modelica language was used to develop these models including Thermofluid library. The development of dynamic models for use in simulation and control of solar thermal central receiver power plant was done with Modelica language (L.J.Yebra,et.al 2006). The model presented could be used in the design of hybrid model predictive control and intelligent control schemes to optimize plant performance, even under start up and shutdown conditions and in the presence of highly variable load disturbances due to daily cycle of solar radiation and passing clouds.

HFLD with TRNSYS

The modeling and simulation of DAHAN, the 1 MW solar thermal central receiver plant in china is under construction at the foot of The Great Wall near Beijing (Zhihao et.al, 2009). The design and construction of DAHAN will demonstrate the operation of central receiver power plant in China. Heliostat field layout design for four configurations and performance calculation of DAHAN is done by software called HFLD developed by China Academy of Sciences. Modeling and simulation of the plant is done with the help of models from TRNSYS library. The simulation of entire plant is still under development.

Table No.2 Summary of the software used for Modeling and Simulation

Name of software	Originating Country	Objective
DELSOL	USA	Incident flux Estimation
MIRVAL	USA	Incident flux Estimation
HELIOS	USA	Incident flux Estimation
UHC	USA	Incident flux Estimation
RADSOLVER	USA	Radiation transfer in cavity receivers
DRAC	USA	Energy absorption in working fluid
CAVITY	USA	Radiation and energy absorption in cavity receivers
HFLCAL	West Germany	Specific calculations of annual performance of heliostats
SAM	USA	Overall system cost and performance
SOLERGY	USA	Performance of Individual components and annual plant performance for each time step considered.
TRNSYS	Spain	Simulation of entire plant annual performance using TRNSYS library.
HFLD with TRNSYS	China	Optimize heliostat field layout, to determine flux Map on receiver aperture

Conclusion

Since 1970s several codes developed have been discussed. This study will help the researchers to select the best suitable software for the simulation of central receiver power plant. According to different specifications and needs of power plants, these softwares can be modified and adopted for simulation. DELSOL, HELIOS, MIRVAL, UHC, softwares can be used for design and performance of heliostat fields. CAVITY, DRAC, FLUENT, RADSOLVER can be used for evaluation of receiver performance whereas energy balance and performance analysis on entire power plant can be done with SAM, SOLERGY, TRNSYS.

CIEMAT (Centro de Investigacione Energeticas Medioambientles Technologicas – Research Centre for Energy Environment and Technology) Laboratory (Pierre et al., 2007) is currently developing a series of tools called SCT (Solar Concentration Toolbox) package under MATLAB software. One tool is dedicated to optical design and optimization of solar receivers, another one to generation of random rays and the last one to central receiver system optimization and performance.

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