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The Simulator of China General Nuclear Power Group (CGNPC) Delingha 50 MW Parabolic Trough Solar Thermal Power Plant

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Abstract. CGN Delingha 50MW parabolic trough solar power plant is China's first commercial trough solar power station. There are 190 heat collecting loops in the solar field of the power plant. Due to the mutual coupling of heat collecting loops layout location, environmental conditions, medium flow, working medium physical property changes and other factors, the hydrodynamic characteristics of the solar field are complex. In practical operation, balancing the flow of the heat absorbing medium in each loop of the large-scale trough solar thermal power plant and stabilizing the outlet medium temperature are difficult problems. Taking CGN Delingha 50MW parabolic trough solar power plant as the research object, this paper adopts the idea of modular modeling to establish the mathematical model of the main equipment in different systems of the power plant, to build the dynamic model of its solar field, steam generation system, heat storage system and steam turbine system. Based on the parallel computing function of the real-time dynamic simulation platform STAR-90, the real-time coupling calculation between different systems is realized. The error of the built model in steady-state is less than 2%, and the dynamic results of the model are in good agreement with the actual operation data. The modeling method in this paper is universal and can be a reference for dynamic modeling of other large-scale trough solar thermal power plants.

Keywords: Concentrating Solar Power (CSP), Parabolic Trough Solar Power Plant, Simulation Model, Dynamic Characteristic

1. Introduction

China has put forward carbon peaking and carbon neutrality goals in 2020, aiming at balancing economic development and green development. The traditional thermal power industry needs to be transformed and upgraded, and under the premise of ensuring social energy demand (residential electricity, industrial electricity, etc.), new energy power generation technology should be vigorously promoted. The energy structure reform should be pushed forward to establish a low-carbon, safe, and efficient energy system based on new energy [1]. The safe and efficient utilization of solar energy can solve the problems of carbon emission, energy shortage and environmental protection [2].

To grasp the dynamic characteristics, there are studies on the simulation and modeling of the system. Frank et al. [3] built the simulation model of trough solar thermal power plant SEGS VI, and simulated the operation in winter and under cloud cover with time steps of one hour. Wagner et al. [4] used TRNSYS to build the physical model and subsystem model of the trough solar thermal power generation system focusing on the influence of different heat transfer fluid inlet temperatures on the system.

China's first 50MW trough solar thermal demonstration power plant (Delingha trough solar thermal power plant) has been in operation for more than three years. Current studies [5-8] on the trough solar thermal systems focus on the dynamic performance of the equipment, the simulation analysis of the system's transient processes, and control methods for the solar field's outlet temperature. Building a dynamic model and conducting simulation experiments are the main means to study the system's dynamic characteristics. Therefore, based on the real-time dynamic model of the heat collector studied by Zhao [9,10], we developed a simulation model for all operating states of Delingha 50MW trough solar thermal power station on the dynamic real-time simulation platform STAR-90.

2. Trough solar thermal power generation system

The trough solar thermal power generation system consists of a solar field with parabolic trough heat collectors, a steam generation system, an energy storage system, and a steam turbine power generation system [11], as shown in Figure 1.

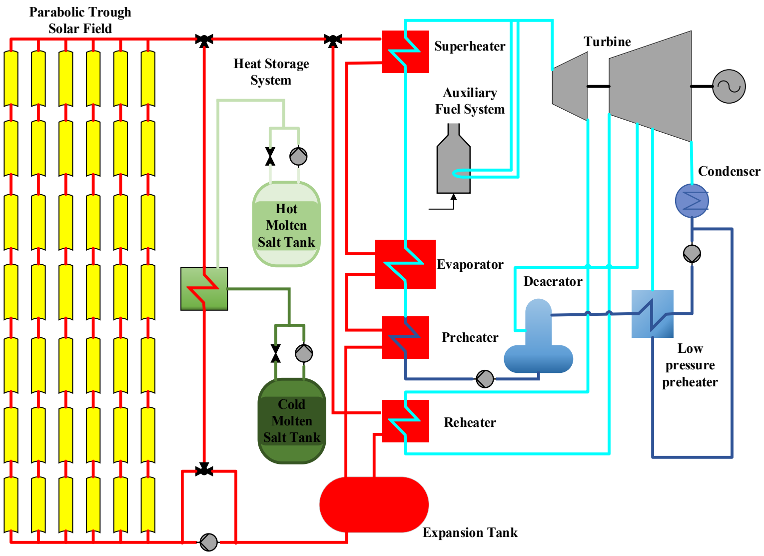

Figure 1. *Trough solar thermal power generation system*

3. Dynamic model of 50 MW trough solar thermal power plant

3.1 Solar field model

The solar field of the Delingha 50 MW trough solar thermal power generation plant consists of 190 heat collecting loops. All the heat collecting loops are in north-south orientation and tracked in east-west direction.

To simulate the flow characteristics of the solar field, a pressure calculation model for the pressure nodes in the flow model's grid is developed based on the law of mass conservation. The pressure node model can handle the process of merging and dividing flows. The medium's change of mass in the node can be expressed as,

$$\frac{\mathrm{d}M}{\mathrm{d}t} = \frac{\mathrm{d}(\rho \times V)}{\mathrm{d}t} = \sum_{i=1}^{n} M_{in,i} - \sum_{i=1}^{n} M_{out,i} \tag{1}$$

Here, M is the mass flow rate, ρ is the density, and V is the volume. Since the density of the heat transfer oil is a function of pressure and temperature, the current pressure P of the node can be expressed as,

$$P = P' + \mathrm{d}t \times \frac{\mathrm{d}P}{V \times d\rho} (\sum_{i=1}^{n} M_{in,i} - \sum_{i=1}^{n} M_{out,i} - V(\frac{d\rho}{dT} \times \frac{\mathrm{d}T}{\mathrm{d}t})) \quad (2)$$

Here, P' is the node pressure at previous moment.

The model of the vacuum absorber tube is shown in Figure 2. In this paper the Monte-Carlo ray tracing method is used, to calculate the flux distribution on the absorber tube.

In the radial direction of the absorber tube, the one-dimensional steady-state energy balance method is used to analyze the heat transfer mechanism of the tube, and only the radial temperature change of the tube is considered. The absorber tube is divided into N parts along the axial direction [12].

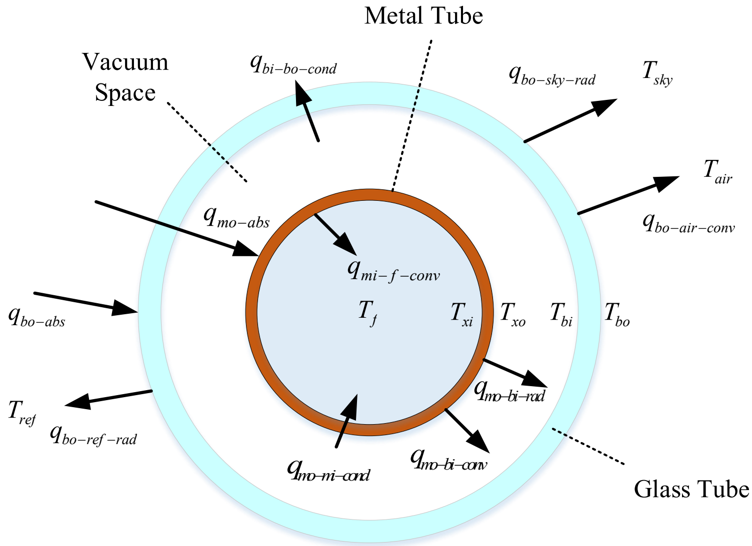

Figure 2. *Model of the vacuum heat absorption tube*

The energy balance of the absorber tube is calculated by,

$$\rho_m c_m V_m \frac{\mathrm{d}T_m}{\mathrm{d}t} = \dot{Q}_{m,abs} - \dot{Q}_{m,f,conv} - \dot{Q}_{m,g,conv} - \dot{Q}_{m,g,rad} \quad (3)$$

Here, subscript *m* stands for metal tube, *abs* means absorbed, *conv* means convection, and *rad* radiation.

The energy balance of the glass tube is calculated by,

$$\rho_g c_g V_g \frac{\mathrm{d}T_g}{\mathrm{d}t} = \dot{Q}_{g,abs} + \dot{Q}_{m,g,conv} + \dot{Q}_{m,g,rad} - \dot{Q}_{g,air,rad} - \dot{Q}_{g,sky,rad} \quad (4)$$

Here, subscript *g* stands for glass tube.

The energy balance of the oil in the vacuum absorber tube is calculated by,

$$\rho_f c_f V_f \frac{\mathrm{d}T_f}{\mathrm{d}t} = \dot{Q}_{m,f,conv} + c_{f,in} m_f T_{f,in} - c_{f,out} m_f T_{f,out} \quad (5)$$

Here, subscript *f* stands for heat transfer fluid.

3.2 Steam generation system model

The steam generation system is equipped with 2 rows of oil-water heat exchangers, through which oil transfers heat to the water-steam system. The main equipment includes: preheater, evaporator, superheater, and reheater. In the actual operation, the oil flow is split into two paths, one of which passes through a three-stage series of heat exchangers (preheater, steam generator, and superheater) to heat the feedwater to produce the main steam, while the other path enters the reheater to reheat the steam after it has done its work in the high-pressure cylinder of turbine. Since the physical state of the water respectively steam in the preheater, superheater, and reheater does not change, a single-phase heat exchanger model is established.

The single-phase heat exchanger model is described for the preheater as example, which is divided into two sides, the heat transfer oil side and the water side. The energy balance for the heat transfer on the oil side is described as follows:

$$\frac{\mathrm{d}(c_{oil} m_{oil} T_{oil})}{\mathrm{d}t} = M_{oil}(h_{oil\_in} - h_{oil,out}) - \dot{Q}_{oil} \tag{6}$$

$$\dot{Q}_{oil} = \alpha_o A_o (T_{oil} - T_{tube}) \tag{7}$$

Here, c is the specific heat capacity, m is the mass, M is mass flow rate, T is temperature, h is enthalpy, α is heat transfer coefficient and A_o is external area of the tube.

For the water side, the energy conservation equation is established:

$$\frac{\mathrm{d}(c_w m_w T_w)}{\mathrm{d}t} = M_w(h_{w,in} - h_{w,out}) - \dot{Q}_w \tag{8}$$

$$\dot{Q}_w = \alpha_i A_i (T_{tube} - T_w) \tag{9}$$

Here, A_i is internal area of the tube and subscript w stands for water.

Heat is exchanged through the wall of the heat transfer tube:

$$\frac{\mathrm{d}(c_{tube} m_{tube} T_{tube})}{\mathrm{d}t} = \dot{Q}_{oil} - \dot{Q}_w \tag{10}$$

In the superheater and reheater model, the water side changes into the steam side.

In the evaporator, water is heated by the oil to generate high-temperature and high-pressure steam. There are three types of work materials: water, steam, and heat transfer oil. The internal space is divided into vapor phase space and liquid phase space to distinguish the calculation. It is necessary to consider the dynamic evaporation process and condensation process to realize the heat transfer and mass change calculation between the liquid phase space and vapor phase space. In addition, the model needs to calculate the change of the water level. If that change is too high that may affect the operational safety of the turbine unit, if it is too low that may affect the operational safety of the heat exchanger tubes. The model sketch of the steam generator is shown in Figure 3.

Establish the energy conservation equation for the heat transfer oil in the heat exchanger tube:

$$\frac{\mathrm{d}(c_{oil} m_{oil} T_{oil})}{\mathrm{d}t} = M_{oil}(h_{oil,in} - h_{oil,out}) - \dot{Q}_{oil} \tag{11}$$

$$\dot{Q}_{oil} = \alpha A_i (T_{oil} - T_{tube}) \tag{12}$$

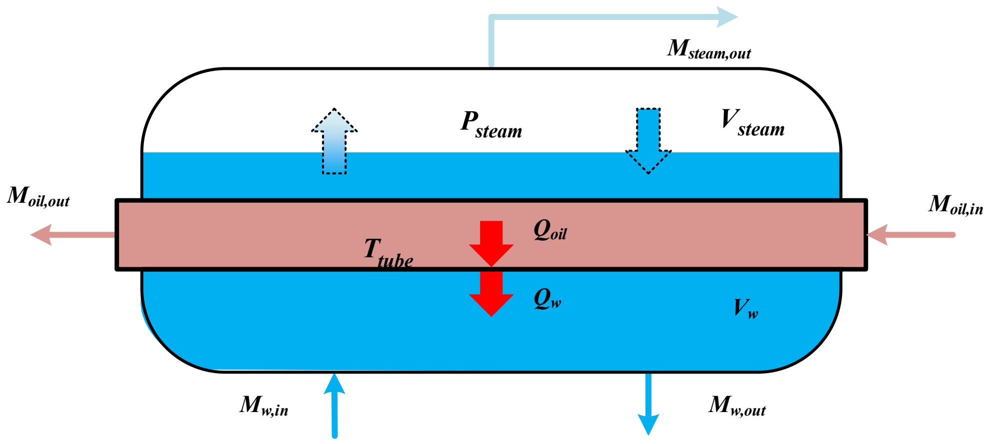

Figure 3. *Model of the evaporator*

Mass conservation equations and energy balance equations are established for the water and the steam:

$$\frac{\mathrm{d}(\rho_w V_w + \rho_{steam} V_{steam})}{\mathrm{d}t} = M_{w,in} - M_{w,out} - M_{steam,out} \tag{13}$$

$$\frac{\mathrm{d}(\rho_w V_w h_w + \rho_{steam} V_{steam} h_{steam})}{\mathrm{d}t} = M_{w,in} h_{w,in} - M_{w,out} h_{w,out} - M_{steam,out} h_{steam} + Q_w \tag{14}$$

The water level is calculated according to the following equation:

$$H_w = \frac{V_w}{S} \tag{15}$$

Heat is exchanged through the wall of the heat transfer tube:

$$\frac{\mathrm{d}(c_{tube} m_{tube} T_{tube})}{\mathrm{d}t} = Q_{oil} - Q_w \tag{16}$$

3.3 Energy storage system model

The main equipment of the energy storage system are salt storage tank and oil/salt heat exchanger. The oil/salt heat exchanger model, is based on the single-phase heat exchanger model in the steam generation system. Since the difference between the high-temperature molten salt tank and the low-temperature molten salt tank is that they store molten salt at different temperatures, no distinction is made in the modeling.

The salt in the storage tank is considered as homogeneously mixed. An energy conservation equation is established for the salt:

$$\frac{\mathrm{d}(c_{salt} m_{salt} T_{salt})}{\mathrm{d}t} = M_{salt\_in} h_{salt\_in} - M_{salt\_out} h_{salt\_out} - \alpha A (T_{salt} - T_{amb}) \tag{17}$$

In addition to the salt temperature, the volume of the salt, which is expressed as the filling level, needs to be monitored to prevent the salt from draining out or overflowing, which could jeopardize the operation safety. The filling level H_{salt} in the molten salt tank is:

$$H_{salt} = \frac{4 m_{salt}}{\rho_{salt} \pi D^2} \tag{18}$$

4. Validation of the model

This paper focuses on verifying the correctness of the model built, which is verified for two aspects: static accuracy and dynamic accuracy.

4.1 Validation of the static characteristics of the solar field model

In order to verify the static characteristics of the built model, the simulation experiment is carried out with the design condition of the actual power plant. The simulation values (SV) and the design values (DV) of the power plant are shown in Table 1. Comparing the simulation results with the theoretical values, it can be seen that the simulation values of the key parameters are basically consistent with the design values, and the error is within 2%.

Table 1. *Main oil parameters configuration of power plant*

		Solar field		**SGS**		**ESS**	
Parameter	Unit	DV	SV	DV	SV	DV	SV
Flow rate	Kg/h	2172492	2177610	952900	968682	2239740	2231136
T_{inlet}	℃	299.3	299	392	393.31	392	392.31
P_{inlet}	MPa	1.98	1.94	1.4	1.38	1.8	1.83
T_{outlet}	℃	393	393.52	301.26	300.03	292	292.56
P_{outlet}	MPa	1.68	1.71	1.22	1.21	1.1	1.17

(SGS stands for steam generation system and ESS for Energy Storage system)

4.2 Validation of the dynamic performance of the solar field model

The simulation simulates the operation process from 12:00 to 15:00 on 20th September, 2021. Figure 4 shows the actual input trends of DNI, wind speed, ambient temperature, and oil inlet temperature in the solar field.

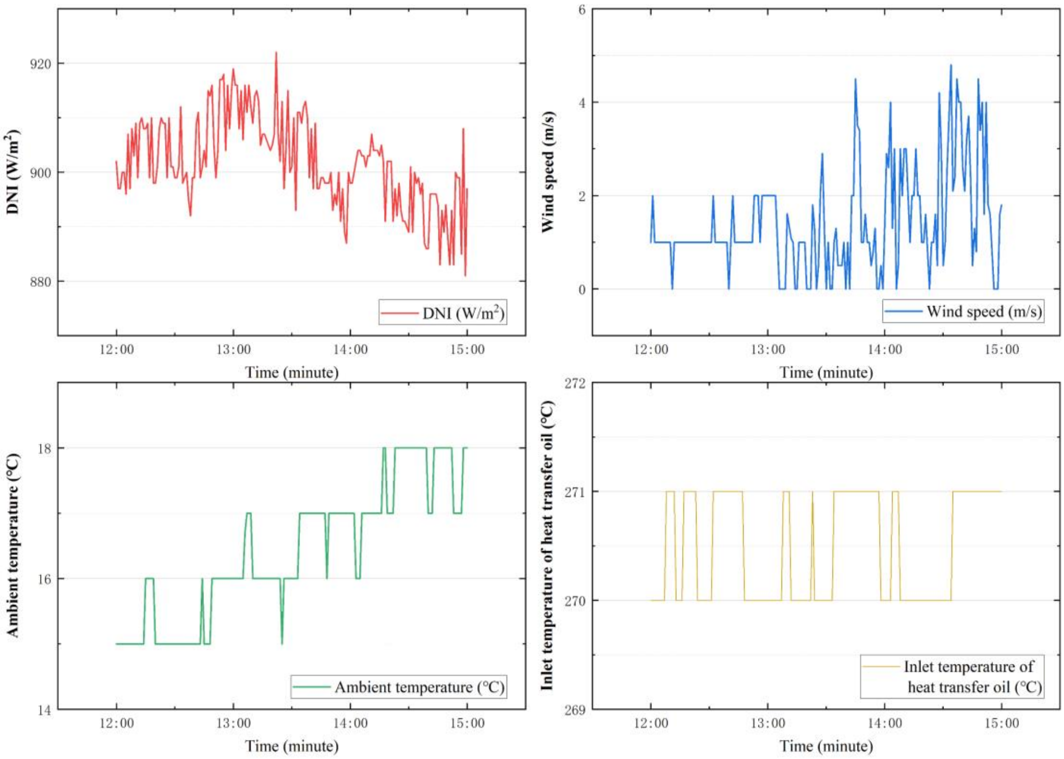

Figure 4. *Variation curve of input parameters*

Figure 5 shows the time-varying curve of the oil's mass flow rate in actual operation on 20th September. The simulated data and operation data are recorded once every 60 seconds.

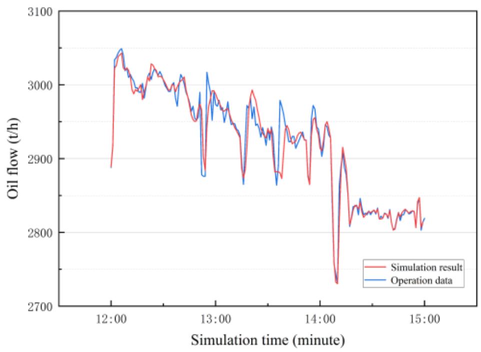

Figure 5. *Comparison diagram of heat transfer oil mass flow rate*

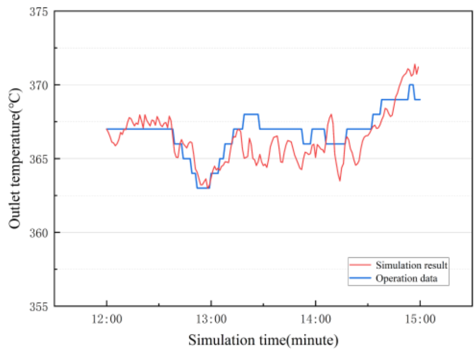

Figure 6. *Comparison diagram of heat transfer oil outlet temperature*

Figure 6 shows the simulation results and the actual operation data of the oil outlet temperature. Table 2 shows relative errors (RE) and absolute errors (AE). The relative error is calculated by $RE = AE/L$, and L is the actual operation data. The maximum difference between the simulation results and the actual operation data is -3.47 ℃, and the maximum error is 0.9 %. The results show that the built model of the Delingha 50 MW parabolic trough solar field has good dynamic accuracy.

Table 2. *Percentage and absolute errors for simulation results and operation data*

Simulation date	**Oil flow rate**		**Oil outlet temperature**	
	AE	**RE**	**AE**	**RE**
20th September	-98 t/h	3.3 %	-3.47℃	0.9 %

5. Conclusion

This paper takes the Delingha 50 MW trough solar thermal power plant as the research object. According to the specific composition and working principle of the system, a dynamic simulation model is established for the solar field, the steam generation system, and the energy storage system. By coupling the built models, a dynamic simulator of Delingha 50 MW trough solar thermal power plant with good accuracy is constructed using the real-time dynamic simulation platform STAR-90. The basic units of the model have been refined to the level of valves and motors, which can reproduce the operation process of the trough solar thermal power system and simulate the energy conversion and transfer process. The built simulator is used to study the dynamic process of trough solar thermal power plant and verify the feasibility of control operation strategies in the future.

In this paper, the constructed system model is verified in terms of static and dynamic accuracies. The static accuracies are no more than 2% of the errors of the main parameters under the rated working conditions, and the dynamic accuracies are compared with the all-day operation data, which proves the accuracy of the constructed Delingha 50 MW trough solar power plant simulator.

Data availability statement

The data underlying this article were provided by CGNPC. Data will be shared on request to the corresponding author with permission of CGNPC.

Author contributions

Lengge Si: Methodology, Software, Formal analysis, Writing- Original draft preparation. **Ershu Xu**: Project administration, Supervision. **Hongjuan Hou:** Supervision.

Competing interests

The authors declare no competing interests.

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