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Dynamic modeling and simulation of parabolic trough solar system

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Abstract

Solar energy has become increasingly distinguished among the renewable resources and solar parabolic trough solar thermal power plants have proved the most mature solar thermal technology by far. In this paper, a dynamic mathematical collector model is established and verified based on the photo-thermal conversion process of parabolic trough collector. Combined the validated model with pumps, oil-water heat exchanger and other existing models, a parabolic trough solar field system is built on the simulation platform. Furthermore, considering the collector loops and solar collector assemblies (SCA), the solar field layout is optimized according to diverse irradiation conditions. In view of one chosen optimum solar field, its dynamic characteristics are tested by the real-time simulation under the disturbances of different irradiation conditions, changeable working medium parameters, etc.

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Keywords: Solar parabolic trough collector; Solar field optimization; Dynamic characteristics

1. Introduction

Solar energy is noted for its cleanness, low-cost, safety and convenience among the renewable resources. It is gaining increasingly attention as an important alternative to cope with energy crisis, climate change and emission reduction. Solar thermal power plants are considered to be an effective way to utilize solar energy on a large scale, of which parabolic trough solar thermal power plants have achieved commercial operations and proved the most mature solar thermal technology by far. Intensive researches and studies have been made. Dudley et al [1-3]

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established models for parabolic trough collector and studied some factors affecting thermal efficiency and heat transfer characteristics. David et al [4, 9, 11] mainly analyzed and discussed the DSG (Direct Steam Generation) collector and its unit thermal characters. Stueltze [6] built a typical solar field and developed the control method. However, most literatures mainly concentrate on the unit steady characteristics of parabolic trough collectors, lacking in the dynamic analysis of heat transfer characteristics of the solar system. Moreover, the physical properties of the working fluid are largely ignored in investigating the factors affecting the system performance. In actual operating, the outdoor climate conditions can not be manually-controlled and the required load often fluctuates, so the solar system is consistently working in a non-steady state and the physical properties of the working fluid varies with its temperature significantly. Therefore, it is necessary to investigate the dynamic characteristics of the solar system considering the impact of the working fluid properties to the system performance.

2. Dynamic collector model and solar field

According to the energy conversion process of parabolic trough collectors, the lumped parameter dynamic model is established and verified by the experimental results [1-2]. Combined the validated dynamic model with the existing pumps, valves, oil-water heat exchanger, storage tank (also the heat storage) and other models, a parabolic trough solar field system is built on the simulation platform, shown in Fig.1. The working fluid is Thermal VP-1 synthesized oil.

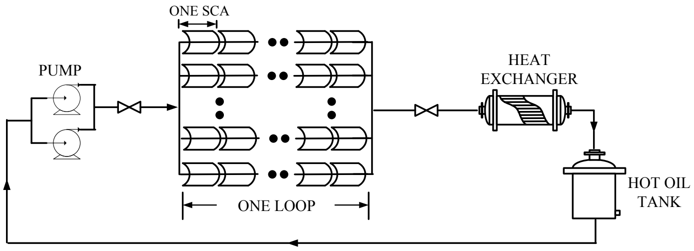


Fig.1. Schematic diagram of parabolic trough solar system

When solar irradiation remains constant, small mass flow rate in one loop contributes to a larger temperature rise of hot oil, less SCA (Solar Collector Assembly) units needed to achieve the specific outlet temperature and less-consumed pump power, but more loops are required under the given total mass flow rate. Contrarily, big mass flow rate of a loop leads to small temperature rise of hot oil and less loops, but more SCA units and pump power. Taking all above factors into account, there exists an optimal loop design and flow distribution under every single solar irradiation.

In one loop, the equivalent efficiency is defined as below and illustrated in Fig 2:

$$\eta = \frac{E - W_{pump} / \eta_e \eta_{pump}}{Q} \quad (1)$$

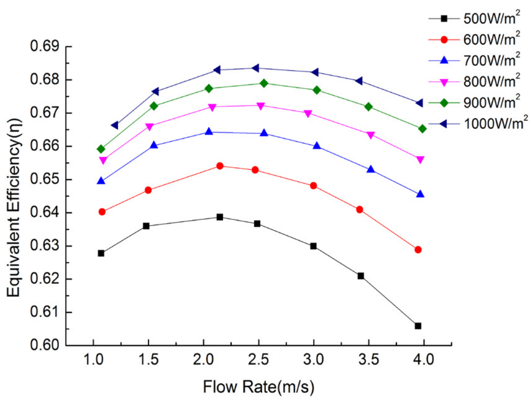
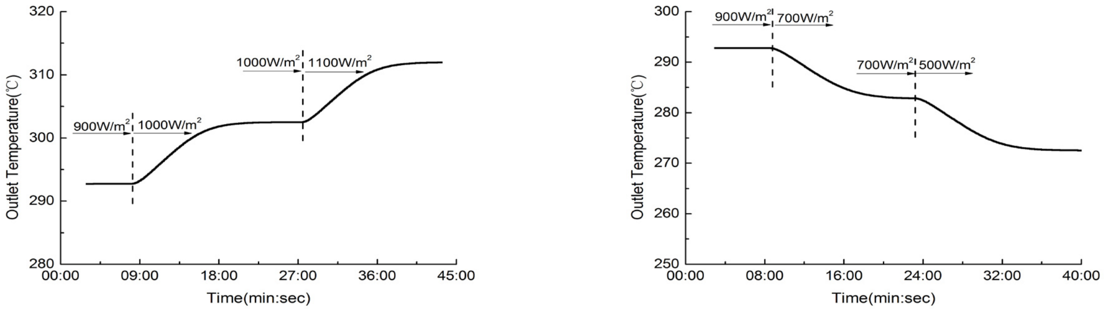


Fig.2. equivalent efficiencies in diverse operating conditions

3. Dynamic characteristics analysis of the solar system

In actual operating, the nominal operating conditions are not always maintained by the solar system. Weather or heat load changes, equipment failure and other disturbances will lead it to variable working states. According to the previous optimum layout analysis, the steady-state operating point of the optimum equivalent efficiency when solar irradiation is 900W/m^2 is selected to further study the dynamic characteristics of the solar system.

3.1. Solar irradiation disturbance

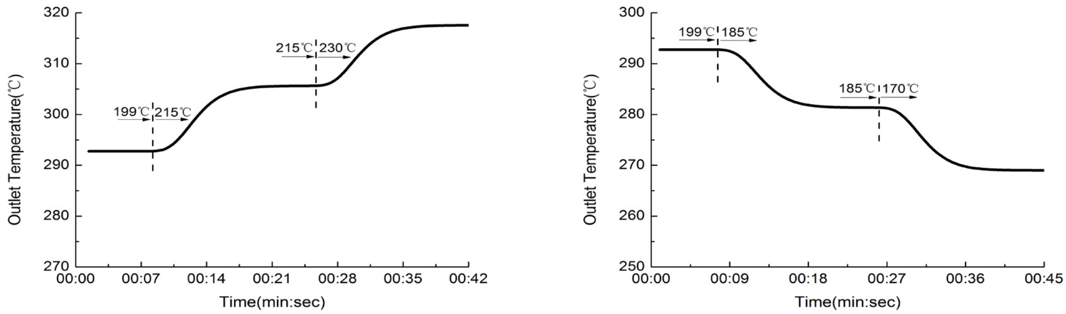


(a) (b)

Fig.3. (a) outlet temperature response to DNI step increase; (b) outlet temperature response to DNI step decrease.

The dynamic response of every SCA's outlet temperature is shown in Fig 3. Comparing the two figures, when solar irradiation step decreases, the heat capacity of hot oil reduces due to the dropping fluid temperature. Thereby, the thermal storage capacity of the whole solar system is weakened and the system is relatively more quickly to achieve a steady state.

3.2. Hot oil inlet temperature disturbance



(a) (b)

Fig.4. (a) outlet temperature response to inlet temperature rise; (b) outlet temperature response to inlet temperature fall.

The above two figures illustrate the outlet temperature dynamic responses to the step-down inlet temperature from 199℃ to 170℃ and the step-up inlet temperature from 199℃ to 230℃ respectively. On average, the outlet temperature changes accordingly with the inlet temperature. When inlet oil temperature increases or decreases by 15 ℃, the outlet temperature rises by 11.8℃ or falls by 12.2℃.

3.3. Hot oil flow rate disturbance

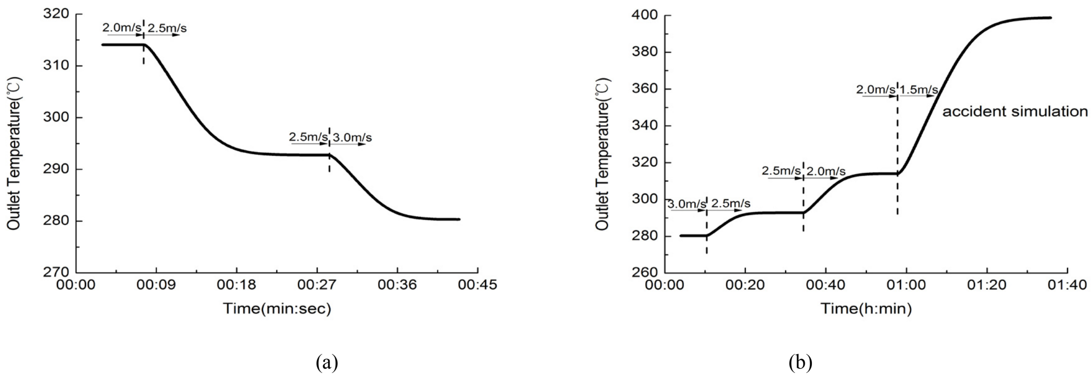


Fig.5. (a) outlet temperature response to flow rate rise; (b) outlet temperature response to flow rate fall.

In the real-time operating, if the valve opening or motor speed changes and the hot oil flow rate step jumps from 2m/s to 2.5m/s, the average outlet temperature drop is 22℃ and the average time constant of the system is about 5.7min. If the hot oil flow rate continues to step increase to 3m/s, the average outlet temperature drop is 12.4℃ and the average time constant is about 5.1min. Contrarily, if the pipes are suddenly blocked or a pump failure occurs, the average time constants of the system are 6.1min and 7.3min when the hot oil flow rate step falls from 3m/s to 2.5m/s and from 2.5m/s to 2m/s by the same decrease amplitude. In the accident simulation, when the hot oil flow rate step drops from 2m/s to 0.9m/s, the outlet temperature can be as high as 399℃ when the whole system stabilizes and the time constant of the system is about 13.5min.

4. Conclusions

In this paper, the photo-thermal conversion process of parabolic trough collectors is analyzed first with the synthesized oil as heat transfer fluid. Then a dynamic mathematical lumped model is established and a complete solar field system is modeled on the simulation platform.

It can be derived from the mathematical modeling and simulation of the parabolic trough solar system, there exist an optimum loop layout and flow distribution under different solar irradiation. The optimum velocities for the discussed scenarios are between 2m/s and 3m/s, with which the whole solar system holds the highest equivalent efficiency. In the dynamic analysis, when solar irradiation step increases from 900W/m^2 to 1100W/m^2 and decreases from 900W/m^2 to 700 W/m^2, the time constant of these scenarios is approximately 6min. On average, the outlet temperature changes accordingly with the inlet temperature. When inlet oil temperature increases or decreases by 15 ℃, the outlet temperature rises by 11.8℃ or falls by 12.2℃. The hot oil temperature changes faster with an increasing flow rate while the temperature variation is larger when the hot oil flow rate is lower. In the accident simulation, if the hot oil flow rate drops to 0.9m/s, the outlet oil temperature will be as high as 399℃ and certain over-temperature risks can be triggered. The time constant of the system in this scenario is 13.5min.

The entire solar system operating can be real-time monitored by the parabolic trough solar field dynamic simulation. Multiple steady or variable operating conditions could be simulated to better grasp the integral performance, which provides some references for running and regulating the solar system under transient operating states.

Acknowledgements

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References

[1] R. Forristall. Heat Transfer Analysis and Modeling of a Parabolic Trough Solar Receiver Implemented in Engineering Equation Solver[R]. Technical Report 2003; NREL/TP-550-34169: 1-26
[2] Dudley V, Kolb G.J, Mahoney A.R, Mancini T.R. Test Results: SEGS LS-2 Solar Collector. Sandia National Laboratories 1994: D-6
[3] Liang Zheng, You Changfu, Dynamic Heat Transfer Characteristics of parabolic solar trough colletors[J]. J.Sol Eng 2009;30(4): 451-456 [in Chinese]
[4] Wei Biao, Zhu Tianyu, Liu Deyou, Simulation of Heat Transfer for Parabolic Trough DSG Solar Collectors[J]. J.Eng Thermophys, 2012;33(3): 474-476 [in Chinese]
[5] Gao Zhichao, Research on System Integration of Parabolic Trough Solar Thermal Power Plants[D]. the Chinese Academy of Sciences, 2011: 3-20 [in Chinese]
[6] Thorsten A. Stuetzle. Automatic Control of the 30MWe SEGS VI Parabolic Trough Plant[D]. University of Wisconsin-Madison 2002: 5-44
[7] B.Kelly, D.Kearney. Parabolic Trough Solar System Piping Model[R]. Subcontract Report 2006. NREL/SR-550-40165: 3-15
[8] Lippke, Frank. Simulation of the Part Load Behavior of a 30MWe SEGS Plant[R]. SAND95-1293, 1995: 7-22
[9] Yan Qin, Hu EJ, Yang Yongping, et al. Dynamic modeling and simulation of a solar direct steam generating system [J], International Journal of Energy Research, 2010
[10] Yan Qin．Thermodynamic characteristic research on solar aided coal-fired power generation system[D], Beijing：North China Electric Power University, 2011 [in Chinese]
[11] David H. Lobon, Emilio Baglietto, Loreto Valenzuela, Eduardo Zarza. Modeling direct steam generation in solar collectors with multiphase CFD[J]. Applied Energy 2014: (113) 1338-1348.
[12] Patnode, ANGELA M. Simulation and Performance Evaluation of Parabolic Trough Solar Power Plants[D]. University of Wisconsin-Madison, 2006: 42-45,162-177.
[13] Guo Su, Liu Deyou, Zhang Yaoming, Xu Chang, Wang Pei. Nonlinear Distributed Parameter Model and Dynamic Characteristics of Parabolic Trough Direct Steam Generation Solar Collectors[J]. Proceedings of the CSEE, 2014 [in Chinese]
[14] Wang Yalong, Research on Parabolic Trough Solar Collector and System Integration Thermal Power[D], the Chinese Academy of Sciences, 2010: 5-10 [in Chinese]