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博 士 学 位 论 文

太阳能光热梯级发电系统设计及其特性研究

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Cascade solar thermal power system design and research of the key features

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摘 要

随着化石能源的消耗和环境问题的凸显,太阳能作为一种新能源,具有分布广泛、总量巨大、取之不竭、无污染的特点,越来越受到世界各国的重视,被广泛认为是未来最有潜力替代传统化石能源的清洁能源。在发电领域,太阳能光热发电是除了太阳能光伏发电之外的另一种发电形式。与光伏发电相比,光热发电因具有发电平稳,电网兼容性友好,易于与现有化石燃料电厂组合等优点而受到越来越多的关注。已经商业应用的太阳能光热发电技术分为槽式集热发电、碟式集热发电和塔式集热发电三种。三种发电技术各有优缺点:槽式集热发电应用最广,成本较低,但效率也较低;碟式集热发电规模较小,多用于分布式发电;塔式集热发电规模较大,成本较高,目前处于快速发展阶段。综合利用现有发电技术的优缺点,在能量梯级收集和能量梯级利用的思想上,提出采用多种集热发电方式的梯级系统,是实现大规模太阳能光热发电的一种新颖的可行的技术方案。

本课题以国家国际合作项目专项“太阳能梯级集热发电系统关键技术合作研究”为背景,目标是研究太阳能光热发电装置,利用各种传统型式的太阳能光热发电系统的优缺点以及热力特性,提出并组建、优化太阳能梯级集热发电系统,为探索出可大规模高效率利用太阳能的光热发电技术提供新的方案。主要研究内容和结论包括:

首先,针对太阳能光热梯级集热发电系统的各部件建立机理模型。依据目标对象的运行机理,根据物理平衡方程,对系统中的各部件,尤其是系统中的关键部件,如集热器、蒸汽产生系统、汽轮机、斯特林机等,建立起数学模型。各部件的数学模型是经由经典理论或是大量实验数据验证的模型,是组建光热梯级集热发电系统模型的基础。对于槽式集热器的集热管和碟式集热器的集热器,建立了热损失模型;对于斯特林机,基于合理的简化和假设,推导出了基于等温传热的斯特林机模型。各部件模型使用 MATLAB 语言编写,采用面向对象的方法,充分利用了继承、多态等特性,保证了各部件之间既具有独立性又具有关联性。

其次,提出太阳能光热梯级集热发电系统的拓扑结构。通过热力特性分析,结合系统中各部件的工作特点,合理布局太阳能光热梯级集热发电系统,利用不同热功循环实现不同品位的能量的梯级利用。合理的梯级发电系统方案才能充分利用发电系统的机理模型,为创建高效率的太阳能光热梯级发电系统提供基础。本文针对各组件的机理模型,组建了多种可行的梯级集热系统拓扑结构。经过系统评估、参数选取、初步计算、方案比较,确定了两种具有代表性的太阳能光热梯级发电系统方案。一种方案同时选用水工质朗肯循环和斯特林循环,利用给水来冷却斯特林机冷腔,回收利用

斯特林机放出的热量；另一种方案选用多级有机工质朗肯循环，利用上一级的凝集热来加热下一级的循环工质，实现能量的梯级利用。

再次，组建太阳能光热梯级集热发电系统模型。根据所选择的太阳能光热梯级发电系统方案，基于建立好的系统中各部件的模型，利用面向对象语言的继承、组合、多态等特点，组建起梯级集热发电系统模型。研究系统在外部及内部因素的耦合作用下主要参数及性能指标的变化规律，掌握其变化机理，建立其性能特性的计算方法。经过组建部件，设置参数，编译环境，完成了各系统方案的系统组建工作，最终完成了拥有自主计算机软件著作权的基于 MATLAB 的太阳能光热梯级发电的模拟系统。系统中各部件相对独立，便于更换或改进部件模型；各系统模型的计算结果可以以单个对象的方式方便地查看系统中各个部件的关键参数。

然后，模拟并优化太阳能光热梯级集热发电系统模型。在太阳能光热梯级发电系统性能特性研究的基础上，对系统进行流程优化、结构重构。具体地，通过对系统的蒸汽发生系统进行分析，提出了分阶段加热方法，通过改变导热油的质量流量降低蒸汽发生系统中的传热温差，有效降低了蒸汽发生系统中换热过程中产生的㶲损，进而可以提高整个系统的效率。针对梯级系统中的斯特林机组，总结了斯特林机组所具有的五种基本排列形式，并分析了各种排列形式下机组的效率和输出功率的差异，得到了给定冷热源流体条件下斯特林机组最佳的排列方式。

最后，优化太阳能光热梯级集热发电系统的运行参数。针对特定结构方案和运行模式，以梯级发电系统的性能参数和经济指标为目标函数，选择合理的可调节参数，确立各种约束条件，利用现代优化方法，如基因算法、蚁群算法，完成系统的参数优化分析，以及对于独立系统的对比分析。分析结果表明，太阳能光热梯级集热发电系统在一定的参数条件下，相比其对应的独立系统，具有更高的总体光电转换效率。在太阳直射强度为 700 W/m^2，碟式集热器出口空气温度为 800 °C 的条件下，方案 1 所选用的太阳能光热梯级集热发电系统比对应的独立系统效率提升 5.2 %，方案 2 所选用的太阳能光热梯级集热发电系统比对应的独立系统效率提升 15.3 %。

关键词： 槽式集热器，碟式集热器，朗肯循环，斯特林循环，斯特林机组，梯级发电

Abstract

With the increasing awareness of the problem of fossil energy consumption and environmental pollution, solar energy as a renewable energy, which has the advantages as widely spreeded, huge amount, inexhaustible, no pollution, has received much attention by many countries and been regarded as the greatest potential candidate of the fossil energy. Concentrated solar thermal power generation is another form of power generation technology except solar photovoltaic power generation. Compared to solar photovoltaic, solar thermal power is gaining more attention for its advantages as smooth power generation, good grid compatibility, easy to combine with existing fossil power plant.

The project of this research is an international cooperation program 'Collaborative research on key technologies to produce electricity by cascade utilisation solar thermal energy'. The objective of the project is to investigate the key scientific problems related to solar heat collector in high temperature, cascade utilisation solar thermal energy with high efficiency, system integration and optimisation to develop the prototype system.

Key words: Parabolic trough collector, Parabolic dish collector, Rankine cycle, Stirling cycle, Stirling engine array, cascade powering

Contents

Nomenclature

Abbreviations

ANN Artificial Neural Network

CCHP Combined cooling, heating and power

CFD Computational Fluid Dynamics

CRTEn Reseach and Technologies Centre of Energy in Borj Cedria

DSG Direct Steam Generation

HTF Heat Transfer Fluid

LM Levenberge Marguardt

LSSVM Least squares support vector machine

MCRT Monte Carlo Ray Tracing

ORC Organic Rankine Cycle

PCG Pola-Ribiere Conjugate Gradient

PTC Parabolic Trough Collector

PTSTPP Parabolic Trough Solar Thermal Power Plant

SCG Scaled Conjugate Gradient

SNL Sandia National Laboratory

SPC Solar parabolic concentrator

SRC Steam Rankine Cycle

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Chapter 1 Introduction

Saving our planet, lifting people out of poverty, advancing economic growth... these are one and the same fight. We must connect the dots between climate change, water scarcity, energy shortages, global health, food security and women's empowerment. Solutions to one problem must be solutions for all.

Ban Ki-moon

This dissertation considers a way to solve the global problems of energy shortage and environment problem.

1.1 Research background and significance

现有太阳能光热发电技术简析,提出太阳能梯级发电的背景及其意义。

1.2 State of the art

(范围的大小)

国内外对太阳能光热发电技术的研究现状。

外文文献-问题-解决方案-本项目需求

1.2.1 Solar Parabolic Trough

Parabolic trough solar technology is the most proven and lowest cost large-scale solar power technology available.[1]

Figure 1-1 shows a parabolic trough product made by Alpha-E.

Padilla[2] performed a detailed one dimensional numerical heat transfer analysis of a PTC (Parabolic Trough Collector). To solve the mathematical model of heat transfer of the

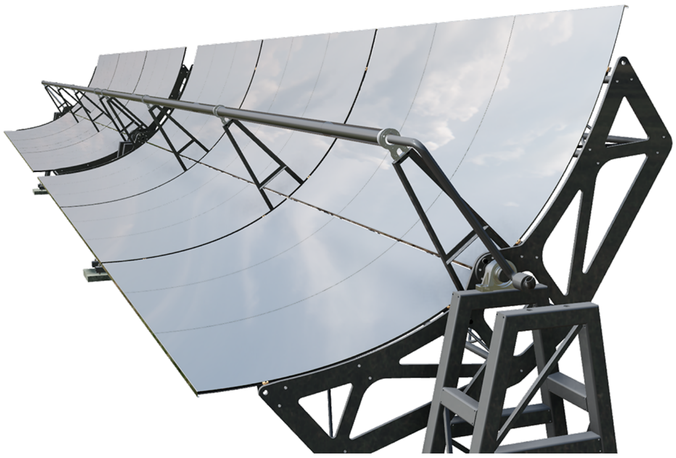

Figure 1-1 Alpha-Trough-350, a parabolic trough product made by Alpha-E

PTC model, the partial differential equations were discretised and the nonlinear algebraic equations were solved simultaneously. The numerical results was validated to the data from Sandia National Laboratory (SNL).

To understand the thermal performance of the collector and identify the heat losses from the collector, Mohamad[3] analysed the temperature variation of the working fluid, tube and glass along the collector.

Guo[4] investigated the energy efficiency and exergy efficiency of the parabolic trough collector. The result shown that there exists an optimal mass flow rate of working fluid for exergy efficiency, and the thermal efficiency and exergy efficiency have opposite changing tendencies under some conditions.

Guo[5] implemented a multi-parameter optimisation of parabolic trough solar receiver based on genetic algorithm where Exergy and thermal efficiencies were employed as objective function.

Padilla[6] performed a comprehensive exergy balance of a parabolic trough collector based on the previous heat transfer model[2]. The results shown that inlet temperature of heat transfer fluid, solar irradiance, and vacuum in annulus have a significant effect on the thermal and exergetic performance, but the effect of wind speed and mass flow rate of heat transfer fluid is negligible. It was obtained that inlet temperature of heat transfer fluid cannot be optimised to achieve simultaneously maximum thermal and exergetic efficiency because they exhibit opposite trends. Finally, it was found that the highest exergy destruction is due to the heat transfer between the sun and the absorber while for exergy losses is due to optical error.

Huang[7] proposed an analytical model for optical performance which employed a modified integration algorithm.

Wang[8] proposed a mathematical model for the optical efficiency of the parabolic trough solar collector and selected three typical regions of solar thermal utilisation in China for the model. The model is validated by comparing the test results in parabolic trough power plant, with relative error range of 1% to about 5%.

Al-Sulaiman[9] presented the exergy analysis of selected thermal power systems driven by PTSCs. The power pf the thermal power system is produced using either a steam Rankine cycle (SRC) or a combined cycle, in which the SRC is the topping cycle and an organic Rankine cycle (ORC) is the bottoming cycle.

Hachicha[10] presented a detailed numerical heat transfer model based on the finite volume method for the parabolic trough collector. This model is based on finite volume method and ray trace techniques and takes into account the finite size of the Sun. The model is thoroughly validated with results from the literature and it shows a good agreement with experimental and analytical results.

Ashouri[11] coupled a small scale parabolic trough collector and a thermal storage tank along with an auxiliary heater to a Kalina cycle to study the performance of the system throughout the year, both thermodynamically and economically.

Guo[12] developed a nonlinear distribution parameter model to model the dynamic behaviours of direct steam generation parabolic trough collector loops under either full or partial solar irradiance disturbance.

Bader[13] developed a numerical model of a tubular vavity-receiver that uses air as the heat transfer fluid. Four different receiver configurations are considered, with smooth or V-corrugated absorber tube and single- or double-glazed aperture window. The different types of energy loss by the collector have been quantified, and the temperature distribution inside the receiver has been studied. The pumping power required to pump the HTF through the receiver has been determined for a 200 m long collector row.

Good[14] proposed solar trough concentrators using air as heat transfer fluid at operating temperatures exceeding 600°C. It consists of an array of helically coiled absorber tubes contained side-by-side within an insulated groove having a rectangular windowed opening. Secondary concentrating optics are incorporated to boost the geometric concentration ratio to 97×.

Boukelia[15] investigated the feed-forward back-propagation learning algorithm with three different variants; Levenberge Marguardt (LM), Scaled Conjugate Gradient (SCG), and Pola-Ribiere Conjugate Gradient (PCG), used in artificial neural network (ANN) to find the best approach for prediction and techno-economic optimization of parabolic trough solar thermal power plant (PTSTPP) integrated with fuel backup system and thermal energy storage.

Kaloudis[16] investigated a PTC system with nano-fluid as the HTF in terms of Computational Fluid Dynamics (CFD). Syltherm 800 liquid oil was used as the HTF, and Al_2O_3 nanoparticles with the concentrations ranges from 0% to 4% was investigated. A boost up to 10% on the collector efficiency was reported for Al_2O_3 concentration of 4%.

Tan[17] proposed a two-stage photovoltaic thermal system based on solar trough concentration is proposed, in which the metal cavity heating stage is added on the basis of the PV/T stage, and thermal energy with higher temperature is output while electric energy is output. The experimental platform of the two-stage photovoltaic thermal system was established, with a 1.8 m^2 mirror PV/T stage and a 15 m^2 mirror heating stage, or a 1.8 m^2 mirror PV/T stage and a 30 m^2 mirror heating stage. The results showed that with single cycle, the long metal cavity heating stage would bring lower thermal efficiency, but temperature rise of the working medium is higher, up to 12.06°C with only single cycle. With 30 min closed multiple cycles, the temperature of the working medium in the water tank was 62.8°C, with an increase of 28.7°C, and thermal energy with higher temperature could be output.

Al-Sulaiman[18] proposed a novel system based on PTC and ORC for combined cooling, heating and power (CCHP). Performance assessment, including efficiency, net electrical power, and electrical to heating and cooling ratios, of the system shown that when CCHP is used, the efficiency increases significantly. This study reveals that the maximum electrical efficiency for the solar mode is 15%, for the solar and storage mode is 7%, and for the storage mode is 6.5%. The maximum CCHP efficiency for the solar mode is 94%, for the solar and storage mode is 47%, and for the storage mode is 42%.

Lobon[19] introduced a computational fluid dynamic simulation approach to predict the behaviour of a solar steam generating system, which is located at the Plataforma Solar de Almeria, Spain. The CFD package STAR-CCM+ code has been used to implement an efficient multiphase model capable of simulating the dynamics of the multiphase fluid in parabolic-trough solar collectors. Numerical and experimental data are compared in a wide range of working conditions.

Xu[20] presented a method to compensate the end loss effect of PTC. An optical analysis on the end loss effect of PTC with horizontal north-south axis (PTC-HNSA) is performed and a five-meter PTC-HNSA experimental system was built. The increased thermal efficiency of the experimental system is measured, and the result that the experimental value (increased thermal efficiency) substantially agreed with the theoretical value (increased optical efficiency) is gained.

Liu[21] developed a mathematical model of PTC using the least squares support vector machine (LSSVM) method. Numerical simulations are implemented to evaluate the feasibility and efficiency of the LSSVM method, where the sample data derived from the experiment and the simulation results of two solar collector systems with 30 m^2 and 600 m^2 solar fields, and the complicated relationship between the solar collector efficiency and the solar flux, the flow rate and the inlet temperature of the heat transfer fluid (HTF) is extracted.

1.2.2 Solar parabolic dish

One of the main goals of the BIOSTIRLING-4SKA project, funded by the European Commission, is the development of a hybrid Dish-Stirling system based on a hybrid solar-gas receiver, which has been designed by the Swedish company Cleanergy.[22]

Craig[23] proposed two types of cooking sections of the solar parabolic dish system: the spiral hot plate copper tube and the heat pipe plate. A conical cavity of copper tubes were put on the focus of the collectors to collect heat and the heat is stored inside an insulated tank which acts both as storage and cooking plate. The use of heat pipes to transfer heat between the oil storage and the cooking pot was compared to the use of a direct natural syphon principle which is achieved using copper tubes in spiral form like electric stove. An accurate theoretical analysis for the heat pipe cooker was achieved by solving the boiling and vaporisation in the evaporator side and then balancing it with the condensation and liquid-vapour interaction in the condenser part while correct heat transfer, pressure and height balancing was calculated in the second experiment. The results show and compare the cooking time, boiling characteristics, overall utilisation efficiencies and necessary comparison between the two system and other existing systems.

Flux distribution of the receiver is simulated successfully by Mao[24] using MCRT method. The impacts of incident solar irradiation, aspect ratio (the ratio of the receiver height to the receiver diameter), and system error on the radiation flux of the receiver are investigated.

Mawire[25] investigated the thermal performance of a cylindrical cavity receiver for an SK-14 parabolic dish concentrator. The receiver exergy rates and efficiencies are found to be appreciably smaller than the receiver energy rates and efficiencies. The exergy factor is found to be high under conditions of high solar radiation and under high operating temperatures. An optical efficiency of around 52% for parabolic dish system is determined under high solar radiation conditions.

Reddy[26,27] performed the theoretical thermal performance analysis of a fuzzy focal solar parabolic dish concentrator with modified cavity receiver. Total heat loss from the modified cavity receiver is estimated considering the effects of wind conditions, operating temperature, emissivity of the cavity cover and thickness of insulation. Time constant test was carried out to determine the influence of sudden change in solar radiation at steady state conditions. The daily performance tests were conducted for different flow rates.

Vikram[28] investigated the total heat losses of modified cavity receiver of SPD with three configurations using 3D numerical model. The effects of various parameters such as diameter ratio, angle of inclination, operating temperature, insulation thickness and emissivity of the cavity cover on the heat losses from the modified vavity receiver are investigated. An ANN model is developed to predict the heat loss for a large set of influencing parameters. Based on ANN modelling, improved Nusselt number correlations are proposed for convective, radiative and total heat losses from the modified cavity receiver. The convective heat losses are greatly influenced by receiver inclination whereas the radiation heat losses are influenced by the cavity cover emissivity. The diameter ratio also plays a major role in heat losses from the cavity receiver. The present method predicts the heat losses more accurately compared with the existing models.

Atul[29] proposed a low-cost solar dish water heating system and investigated the effect of variation of mass flow rate on performance of the heater prototype. A novel truncated cone-shaped helical coiled receiver made up of copper is put at the focal point of SP.

CRTEn developed a solar parabolic concentrator (SPC) using four types of absorbers: flat plat, disk, water calorimeter and solar heat exchanger.[30] For the system different types of absorbers, experiments were conducted to obtain the mean concentration ratio and both energy and exergy efficiency. Results shown that thermal energy efficiency of the system varies from 40 % to 77 %, the concentrating system reaches an average exergy efficiency of 50 % and a concentration factor around 178.

Blazquez[22]

Uma[31]

Patil[32] described the development of automatic dual axis solar tracking system for solar parabolic dish. Five light dependent resistors were used to sense the sunlight and Two permanent magnet DC motors are used to move the solar dish. A controller software were developed to control the motors using the data sensed by the resistors.

Pavlovic[33] presented a procedure to design a square facet concentrator for laboratory-scale research on medium-temperature thermal processes. A parabolic collector made up of individual square mirror panels (facets) were investigated. These facets can deliver up to 13.604 kW radiative power over a 250 mm radius disk (receiver) with average concentrating ratio exceeding 1200.

1.2.3 Solar Tower

1.2.4 Rankine cycle

1.2.5 Stirling cycle

1.2.6 Brayton cycle

1.3 Research objective

(改进点,重点,难度)

1.4 Research methods

(技术路线)

Chapter 2　System topology design

利用热力学原理进行定性分析。提炼出创新点。

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2.2　Cascade utilisation

2.3　System topology selection

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3.1.4.4 Deaerator

3.1.4.5 Thermal storage system

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3.3 Determination of state parameters

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3.5 Steam extraction and regeneration system

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Chapter 5 Optimization of steam generating system

Chapter 6 Cascade system performance evaluation

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6.2 Determination of system parameters

6.3 Stand-alone system selection

6.4 Comparison with stand-alone system

6.5 System analysis

Chapter 7 Conclusion and outlook

7.1 Conclusion

7.2 Innovation

7.3 Outlook

Acknowledge

This is the acknowledgement part.

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Appendix A　Publication

[1] Zhang Cheng, Kun Wang. International Conference on Power Engineering: ICOPE 2013: FEA simulation on the alignment of the shafts of three-fulcrum turbine.

[2] Performance comparison of new and traditional arrangements of a dish-Stirling system

[3] A multi-stage exergy-loss reduction system for solar parabolic trough power plants

[4] Cascade system using both trough system and dish system for power generation

[5] A solar thermal cascade system, No. 201610806296.5

[6] A flow control method used in a multi-stage heating system, No. 201610805604.2

Appendix B　Formulae

The is the content of the Appendix B