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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和多种热功循环的梯级系统,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,推导出了考虑了各种热损失和不可逆因素的斯特林机模型。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 problem of fossil energy consumption and environmental pollution, solar energy as a renewable energy, which has the advantages of widely distribution, huge amount, inexhaustible and no pollution, has received much attention by many countries and been regarded as the best 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 integrate with existing fossil power plant.

Commercial solar thermal power generation technology is divided into trough collector power generation, dish collector power generation and solar tower power generation. These three types of power generation technologies have their own advantages and disadvantages: trough collector power generation is the most widely used one, its cost is low, however its efficiency is also low; dish collector power generation has high efficiency and smaller capacity, it is used for distributed generation widely; solar tower generation, which has large scales, high efficiency and high cost, is currently in rapid development stage. Based on the idea of energy cascade collection and energy cascade utilization, this paper proposed a cascade system that uses different collector power generation methods and different thermodynamic cycles, which may be a new and feasible technology to realize large-scale solar thermal power generation.

The research is based on the national cooperation project "Collaborative research on key technologies to produce electricity by cascade utilization solar thermal energy" as the background. The objective of this project is to research the equipment of solar thermal power generation system, to propose, develop and optimize a solar thermal cascade system depending on the advantages and disadvantages of the solar thermal power generation system, and to explore a new feasible technology for large-scale solar thermal power generation. The main contents and conclusions of this paper are as follows:

Firstly, mechanism models were established for the components of solar thermal power generation system. The mechanism mathematical models were developed according to the operation mechanism of the target object and physical equations. The key components in the system, such as collectors, steam generating system, steam turbine and Stirling engine, were

modeled with details. The mathematical model of each component is a model verified by the classical theory or a large number of experimental data, which is the basic of the model of the cascade solar thermal power generation system. Heat loss models were established for the receivers of trough collector and dish collector. For the Stirling engine, based on the reasonable simplification and hypothesis, the model of the Stirling machine considered various losses and irrevisibilities was developed. The component models were developed in MATLAB by using object-oriented method. It makes full use of inheritance and polymorphism to ensure both the independence and the relevance of the components.

Secondly, the topological structure of solar thermal cascade power generation system was proposed. According to the analysis of thermal characteristics and the working characteristics of each component in the system, rationally arranged topological structures of cascade system were proposed. These systems use different thermodynamic cycles to utilize energy in different temperature zones. A reasonable cascade generation system can make full use of the mechanism models of the power generation system and provide the foundation for higher efficiency solar thermal cascade generation systems. In this paper, several schemes of feasible topological structures of solar thermal cascade system were set up according to the mechanism model of each component. After system evaluation, parameter selection, preliminary calculation and scheme comparison, two representative typical schemes were determined. In one scheme, both Rankine cycle (water as the working fluid) and Stirling cycle are used for power generation. Cooling water of the Rankine cycle is used to cool the hot end of the Stirling engines to recover the released heat. In the other scheme, multiple organic Rankine cycles are used for power generation. Condensation heat of upper cycle is absorbed by lower cycle for energy cascade utilization.

Thirdly, the solar thermal cascade generation system models were developed. Based on the selected solar thermal cascade generation systems, solar thermal cascade generation system models were established based on the model of each component in the systems. The object-oriented features of inheritance, combination and polymorphism were used for the model development. The change rules of the main parameters and the performance indexes under the coupling of external and internal factors were studied. The change mechanism was studied and the calculation method of its performance characteristics was established. After setting up the components, setting the parameters and compiling the environment, the paper completes the system construction of each system scheme, and finally completes the simulation system of solar thermal cascade generation based on MATLAB with the copyright of independent computer software. The system components are relatively independent, easy

to replace or improve the parts model; the results of the calculation of the system model can be a single object to easily view the various components of the system key parameters.

Then, simulation and optimization of cascade solar thermal power generation system model. Based on the study of the performance characteristics of solar thermal cascade generation system, the system is optimized and the structure is reconstructed. In particular, by analyzing the steam generation system of the system, a method of staged heating is proposed to reduce the heat transfer temperature difference in the steam generating system by changing the mass flow rate of the heat conduction oil, effectively reducing the heat generated during the heat exchange process in the steam generating system. Which can improve the efficiency of the whole system. Based on Stirling unit in cascade system, five kinds of basic arrangement forms of Stirling unit are summarized, and the difference of unit efficiency and output power under various arrangement forms is analyzed, and a given cold and heat source fluid Stirling unit under the conditions of the best arrangement.

Finally, the operating parameters of solar thermal cascade power generation system are optimized. According to the specific structural scheme and operation mode, the performance parameters and economic indexes of the cascade generation system are taken as the objective function, reasonable adjustable parameters are selected, various constraints are established, and modern optimization methods such as genetic algorithm and ant colony algorithm are used to complete the system Parameter optimization analysis, as well as the independent system for comparative analysis. The results show that solar thermal cascade power generation system has higher overall photoelectric conversion efficiency under certain parameter conditions than its corresponding independent system. Under the condition of direct solar radiation intensity of 700 $\mathrm{W/m^2}$ and dish type collector outlet air temperature of 800°C, the solar thermal cascade power generation system of Scheme 1 is better than the corresponding The efficiency of stand-alone system is increased by 5.2%. The solar thermal cascade power generation system selected in Scheme 2 is 15.3% more efficient than the corresponding independent system.

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

Contents

Nomenclature

$\overline{d_{cav}}$ Effective diameter of the cavity, m

A heat transfer area (m^2)

A heat transfer area (m^2)

$A_{dc,1}$ Heat transfer area of dish receiver between tube and air, m^2

$A_{se,1}$ Heat transfer area of Stirling engine at air side, m^2

$A_{se,2}$ Heat transfer area of Stirling engine at water side, m^2

c_p specific heat at constant pressure ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)

c_p specific heat at constant pressure ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)

c_r Heat transfer correction factor of coiled tube of volumetric receiver

c_v specific heat at constant volume ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)

c_v specific heat at constant volume ($J{\cdot}kg^{-1}{\cdot}K^{-1}$)

d Diameter, m

d_i Inner diameter of trough receiver, m

dep Depth, m

e regenerator effectiveness

e regenerator effectiveness

J annular gap cylinder displacer (m)

J annular gap cylinder displacer (m)

K Incidence angle modifier of trough collector

K dead volume factor

K dead volume factor

k Specific heat ratio

k specific heat ratio (c_p/c_v), thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)

k specific heat ratio (c_p/c_v), thermal conductivity ($\mathrm{W \cdot m^{-1} \cdot K^{-1}}$)

k_{insu} Thermal conductivity of air at the temperature of outside insulating layer, W/(m·K)

m mass of working fluid in Stirling engine (kg)

m mass of working fluid in Stirling engine (kg)

n_g Amount of working gas in each Stirling engine, mol

n_{se} Number of Stirling engines in the Stirling engine array

n_{se} number of Stirling engine in SEA

n_{se} number of Stirling engine in SEA

Nu Nusselt number

P power of Stirling engine (W)

P power of Stirling engine (W)

p pressure (Pa)

p pressure (Pa)

Pr Prandtl number

Q absorbed heat (J)

Q absorbed heat (J)

q'' Heat flux, $\mathrm{W/m^2}$

q_m mass flow rate ($\mathrm{kg \cdot s^{-1}}$)

q_m mass flow rate (kg·s^{-1})

$q_{cond,tot}$ Total conduction loss

$q_{conv,tot}$ Total convection loss

$q_{dc,1}$ Energy absorbed by air in the dish collector

q_{in} Solar energy launched into dish receiver aperture, W

$q_{rad,emit}$ Radiation emitted by dish receiver

$q_{rad,reflect}$ Reflected radiation by volumetric receiver, W

R gas constant (J·kg^{-1}·K^{-1})

R gas constant (J·kg^{-1}·K^{-1})

Re Reynolds number

s_{se} speed of Stirling engine (Hz)

s_{se} speed of Stirling engine (Hz)

T_H working fluid temperature in the hot space (K)

T_H working fluid temperature in the hot space (K)

T_L working fluid temperature in the cold space (K)

T_L working fluid temperature in the cold space (K)

T_R effective working fluid temperature in regenerator (K)

T_R effective working fluid temperature in regenerator (K)

T_w wall temperature (K)

T_w wall temperature (K)

T_{insu} Temperature of insulating outside layer, K

U Overall heat transfer coefficient, W/(m^2·K)

U overall heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)

U overall heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)

V_C compression volume (m^3)

V_C compression volume (m^3)

V_D total dead volume (m^3)

V_D total dead volume (m^3)

V_E expansion volume (m^3)

V_E expansion volume (m^3)

V_{DC} cold space dead volume (m^3)

V_{DC} cold space dead volume (m^3)

V_{DH} hot space dead volume (m^3)

V_{DH} hot space dead volume (m^3)

V_{DR} regenerator dead volume (m^3)

V_{DR} regenerator dead volume (m^3)

W output work (J)

W output work (J)

Z displacer stroke (m)

Z displacer stroke (m)

Abbreviations

ANN Artificial Neural Network

CCHP Combined cooling, heating and power

CFD Computational Fluid Dynamics

CPC Compound parabolic collector

CRTEn Research and Technologies Centre of Energy in Borj Cedria

DSG Direct Steam Generation

HTF Heat Transfer Fluid

ISCC Integrated Solar Combined Cycle

LFC Linear Fresnel Collector

LM Levenberge Marguardt

LSSVM Least squares support vector machine

MCRT Monte Carlo Ray Tracing

ORC Organic Rankine Cycle

ORC Organic Rankine Cycle

PCG Pola-Ribiere Conjugate Gradient

PTC Parabolic Trough Collector

PTC Parabolic Trough Collector

PTSTPP Parabolic Trough Solar Thermal Power Plant

SCG Scaled Conjugate Gradient

SEA Stirling engine array

SNL Sandia National Laboratory

SPC Solar parabolic concentrator

SRC Steam Rankine Cycle

SRC Steam Rankine Cycle

Greek Symbols

α Absorptance

δ Thickness, m

ϵ Emissivity

η Thermal efficiency

$\eta_{shading}$ Shading factor

γ Intercept factor; compression ratio

γ_H space ratio in process 12

γ_H space ratio in process 12

γ_L space ratio in process 34

γ_L space ratio in process 34

λ Thermal conductivity, $\mathrm{W/(m \cdot K)}$

μ Viscosity, kg/(m·s)

μ dynamic viscosity ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$)

μ dynamic viscosity ($\mathrm{kg \cdot m^{-1} \cdot s^{-1}}$)

ρ Reflectivity

θ_{dc} Dish aperture angle (0° is horizontal, 90° is vertically down)

Subscripts

ap Aperture of the dish receiver

c cooling fluid

c cooling fluid

cav Cavity of the dish receiver

cw cooler wall

cw cooler wall

eff Effective parameter of the dish receiver cavity

h heating fluid

h heating fluid

hw heater wall

hw heater wall

i inlet

i inlet

$insu$ insulating layer

o outlet

o outlet

p piston

p piston

r regenerator

r regenerator

th theoretical

th theoretical

w Tube wall

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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

REN21, a global renewable energy policy multi-stakeholder network, published the most comprehensive annual overview of renewable energy of 2016. Renewables are now established around the world as mainstream sources of energy. Rapid growth, particularly in the power sector, is driven by several factors, including the improving cost-competiveness of renewable technologies, dedicated policy initiatives, better access to financing, energy security and environmental concerns, growing demand for energy in developing and emerging economies, and the need for access to modern energy. An estimated 147 gigawatts (GW) of renewable power capacity was added in 2015.

Concentrating solar power technologies use different mirror configurations to concentrate the sun's light energy onto a receiver and convert it into heat. The heat can then be used to create steam to drive a turbine to produce electrical power or used as industrial process heat.

Concentrating solar power plants can integrate thermal energy storage systems to generate electricity during cloudy periods or even several hours after the sunset. CSP systems can be also combined with combined cycle power plants resulting in hybrid power plants which provide high-value, dispatch-able power. These attributes, make concentrating solar power the most attractive renewable energy option in the Sunbelt regions.

There are four types of CSP technologies being applied. For each of these, there are various design variations or different configurations.

In addition to wind and photovoltaic power, concentrating solar thermal power (CSP) will make a major contribution to electricity provision from renewable energies. Drawing on almost 30 years of operational experience in the multi-megawatt range, CSP is now a proven technology with a reliable cost and performance record. In conjunction with thermal energy storage, electricity can be provided according to demand. To date, solar thermal power plants with a total capacity of 1.3 GW are in operation worldwide, with an additional 2.3 GW under construction and 31.7 GW in advanced planning stage. Depending on the concentration factors, temperatures up to 1000°C can be reached to produce saturated or superheated steam for steam turbine cycles or compressed hot gas for gas turbine cycles. The heat rejected from these thermodynamic cycles can be used for sea water desalination, process heat and centralized provision of chilled water. While electricity generation from CSP plants is still more expensive than from wind turbines or photovoltaic panels, its independence from fluctuations and daily variation of wind speed and solar radiation provides it with a higher value. To become competitive with mid-load electricity from conventional power plants within the next 10−15 years, mass production of components, increased plant size and planning/operating experience will be accompanied by technological innovations. On 30 October 2009, a number of major industrial companies joined forces to establish the so-called DESERTEC Industry Initiative, which aims at providing by 2050 15 per cent of European electricity from renewable energy sources in North Africa, while at the same time securing energy, water, income and employment for this region. Solar thermal power plants are in the heart of this concept.

1.2 State of the art

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.

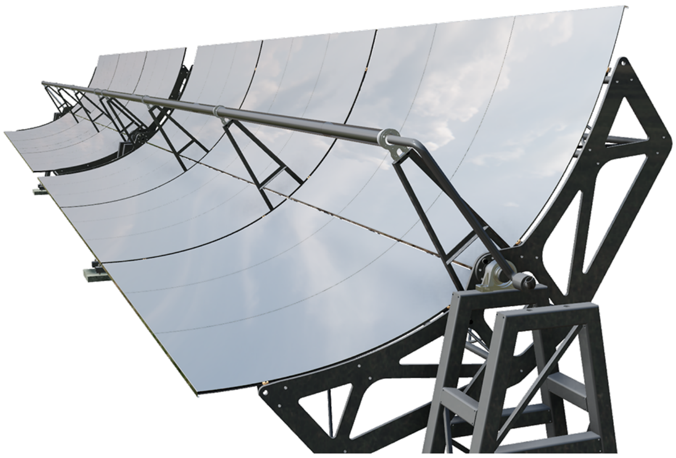

Figure 1-1 Alpha-Trough-350, a parabolic trough product made by Alpha-E

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 PTC model, the partial differential equations were discretized 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] analyzed 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 optimization 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 optimized 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 utilization 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 behaviors 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 nanofluid 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 behavior 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 vaporization in the evaporator side and then balancing it with the condensation and liquid-vapor 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 utilization 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 modeling, 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] studied the optimization of the concentrator and receiver cavity geometry of parabolic dish system. Ray-tracing analysis has been performed with the open source software Tonatiuh, a ray-tracing tool specifically oriented to the modeling of solar concentrators.

Uma[31] carried out the simulation of the structural, thermal and CFD analysis of the dish with varying metallic properties (Aluminium, Copper and StainlessSteel) under different wind conditions. Computational Fluid Dynamics (CFD) was done to simulate the thermal performance of the dish at two different wind velocities.

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 dish receiver with average concentrating ratio exceeding 1200.

1.2.3 Solar Tower

Besarati and Yogi[34]

A number of codes have been developed in order to optimize the heliostat field layout for solar power tower plants. These codes are intended to improve calculation accuracy as well as computational time. Of all the factors that need to be taken into account in these codes, shading and blocking calculations introduce significant complexity as they are computationally intensive. In this paper, a new and simple method is proposed to identify the heliostats with the greatest potential for shadowing and blocking a heliostat. Using the new method, the computational time is considerably reduced as unnecessary calculations are avoided. The Sassi method is then used to calculate the shading and blocking efficiency. The results are compared with the literature and good agreement is obtained. As a case study, the paper also investigates optimization of a 50 MWth heliostat field layout for Dagget, California. Yearly insolation weighted efficiency is selected as the objective function while two parameters of the prophylaxis pattern, which define the shape of the field layout, are the design variables. The acceptance angle of the cavity receiver and distance between the adjacent heliostats are the physical constraints which are included in the optimization. The optimization algorithm is explained in detail and the optimal field layout is presented.

Haroun[35] The aim of this work was to propose a novel system combines both solar chimney and thermo siphon solar tower systems. To this end, theoretical study to the proposed system was conducted. In this new system, the solar tower was installed at the exit of the solar chimney. The results of the theoretical study showed that, the new system generates more power compared with the conventional system. It was found that the maximum power extracted from the new system was about two times that obtained from the conventional system at the same height, for the specified range studied in this work. In addition, it was found that the new system has higher overall efficiency and generates higher speeds of air at the chimney inlet. This increase in both maximum power and air speed at the chimney inlet from the new system is enhanced with the rise in solar irradiance, radius of collector, and ratio of solar tower height to solar chimney height. Moreover, the results indicated that there is a certain ratio between solar tower length and width at which the maximum extracted mechanical power reached a maximum value for the specified parameters of solar irradiance, collector radius, height of chimney, and height of solar tower.

Franchini et al.[36] Simulations were carried out to predict the performance of a Solar Rankine Cycle (SRC) and an Integrated Solar Combined Cycle (ISCC) when combined with two different solar field configurations based on parabolic trough and power tower systems. For the selected cases, yearly plant performance was computed under real operating conditions on a one hour basis. A computing procedure was developed by integrating two commercial softwares with in-house computer code. Thermodynamic performance was featured for every plant configuration both at nominal and part load conditions. A single reheat regenerative Rankine cycle was chosen for the SRC plant whereas a commercial gas turbine, i.e. Siemens SGT-800, with a dual pressure heat recovery steam generator (HRSG) was assumed for the ISCC plant. As far as the heat transfer fluid (HTF) is concerned, molten salt was chosen to transfer heat to the water loop in the SRC. Synthetic oil was considered in the ISCC plant. Plants were assumed to be located in a Southern Spain site. The comparative analysis was mainly focused on the influence of CSP technology on global solar energy conversion efficiency of both SRC and ISCC plants. Special attention was devoted to assess trough collectors (PTCs) against the solar tower (ST) system in terms of intercepted radiation and thermal power sent to the power block. The ISCC coupled with a ST was found to assure the highest annual solar-to-electric efficiency of 21.8%. This is the result of both higher collection efficiency of ST compared to PTCs and higher conversion efficiency of solar energy introduced into the combined cycle, as compared to SRC.

Kim et al.[37] Heat loss is an important factor in predicting the performance of solar receiver of concentrated solar power (CSP) systems. This study presents a numerical simulation calculating convection and radiation heat losses from four different receiver shapes including external and cavity type receivers with different opening ratios (ratio of cavity aperture area to receiver area). The simulation was carried out using Fluent {CFD} (computational fluid dynamics) software considering three different receiver temperatures (600, 750, and 900 °C), three wind velocities (1, 5, and 10 m/s), and two wind directions (head-on and side-on). The simulation results were then used for deriving a simplified correlation model which gives the fraction of convection heat loss by a function of opening ratio, receiver temperature, and wind velocity. The calculated fraction can be easily converted to convection heat loss, total heat loss, or receiver efficiency once the radiation heat loss is estimated by any applicable prediction model. Calculated heat loses by the proposed simple correlation model showed good agreements with the simulation results with 11.4% and 5.9% average absolute deviations for convection heat loss and total heat loss, respectively. Validation of the model with experimental data was also carried out using test results available from three central receiver systems (Martin Marietta, Solar One and Solar Two).

Lara et al.[38] A novel modeling tool for calculation of central receiver concentrated flux distributions is presented, which takes into account drift effects. This tool is based on a drift model that includes different geometrical error sources in a rigorous manner and on a simple analytic approximation for the individual flux distribution of a heliostat. The model is applied to a group of heliostats of a real field to obtain the resulting flux distribution and its variation along the day. The distributions differ strongly from those obtained assuming the ideal case without drift or a case with a Gaussian tracking error function. The time evolution of peak flux is also calculated to demonstrate the capabilities of the model. The evolution of this parameter also shows strong differences in comparison to the case without drift.

Ramos[39] A method for optimizing a central receiver solar thermal electric power plant is studied. We parametrize the plant design as a function of eleven design variables and reduce the problem of finding optimal designs to the numerical problem of finding the minimum of a function of several variables. This minimization problem is attacked with different algorithms both local and global in nature. We find that all algorithms find the same minimum of the objective function. The performance of each of the algorithms and the resulting designs are studied for two typical cases. We describe a method to evaluate the impact of design variables in the plant performance. This method will tell us what variables are key to the optimal plant design and which ones are less important. This information can be used to further improve the plant design and to accelerate the optimization procedure.

Wei et al.[40] A new method for the design of the heliostat field layout for solar tower power plant is proposed. In the new method, the heliostat boundary is constrained by the receiver geometrical aperture and the efficiency factor which is the product of the annual cosine efficiency and the annual atmospheric transmission efficiency of heliostat. With the new method, the annual interception efficiency does not need to be calculated when places the heliostats, therefore the total time of design and optimization is saved significantly. Based on the new method, a new code for heliostat field layout design (HFLD) has been developed and a new heliostat field layout for the PS10 plant at the PS10 location has been designed by using the new code. Compared with current PS10 layout, the new designed heliostats have the same optical efficiency but with a faster response speed. In addition, to evaluate the feasibility of crops growth on the field land under heliostats, a new calculation method for the annual sunshine duration on the land surface is proposed as well. ?? 2010 Elsevier Ltd. All rights reserved.

Wei et al.[41] A new code for the design and analysis of the heliostat field layout for power tower system is developed. In the new code, a new method for the heliostat field layout is proposed based on the edge ray principle of nonimaging optics. The heliostat field boundary is constrained by the tower height, the receiver tilt angle and size and the heliostat efficiency factor which is the product of the annual cosine efficiency and the annual atmospheric transmission efficiency. With the new method, the heliostat can be placed with a higher efficiency and a faster response speed of the design and optimization can be obtained. A new module for the analysis of the aspherical heliostat is created in the new code. A new toroidal heliostat field is designed and analyzed by using the new code. Compared with the spherical heliostat, the solar image radius of the field is reduced by about 30% by using the toroidal heliostat if the mirror shape and the tracking are ideal. In addition, to maximize the utilization of land, suitable crops can be considered to be planted under heliostats. To evaluate the feasibility of the crop growth, a method for calculating the annual distribution of sunshine duration on the land surface is developed as well.

Xu et al.[42] 1 MW Dahan solar thermal power tower plant is modeled from mathematical models for all of the working conditions using the modular modeling method. The dynamic and static characteristics of the power plant are analyzed based on these models. Response curves of the system state parameters are given for different solar irradiance disturbances. Conclusions in this paper are good references for the design of solar thermal power tower plant.

Xu et al.[43] In this paper, the thermal energy storage system of Badaling 1 MW solar power tower plant is modeled from mathematical models for whole of the working conditions using the modular modeling method. This model can accurately simulate the recharge and discharge processes of thermal energy storage system. The dynamic and static characteristics of the thermal energy storage system are analyzed based on the model response curves of the system state parameters that are obtained from different steam flow disturbances. Conclusions of this paper are good references for the design, operating, and control strategy of solar thermal power plant.

1.3 Research Objective

1.4 Research Methods

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] Zhang Cheng, Zhang Yanping, Arauzo Inmaculada, Gao Wei, Zou Chongzhe. Cascade system using both trough system and dish system for power generation. Energy Convers Manag 2017;142:494–503. doi:10.1016/j.enconman.2017.03.073.

[5] Thermal Modeling of a Pressurized Air Cavity Receiver for a Solar Dish Stirling System

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

[7] 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