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Cascade system using both trough system and dish system for power generation

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ABSTRACT

This paper represents a novel solar thermal cascade system using both trough and dish systems for power generation. An effective structure using the condensed fluid of Rankine cycle to cool the Stirling engines to use the heat released by Stirling engines was proposed. The cascade system model with different fluid circuits was developed. The models of some important components of the system, such as dish collector, trough collector and Stirling engine array, are presented with detail explanation in this paper. Corresponding stand-alone systems were also developed for comparison. Simulations were conducted with the models to find out efficiency difference between cascade system and corresponding stand-alone systems. The directions to increase the efficiency difference were also considered. Results show that the cascade system can achieve a higher efficiency with a high solar irradiance (>550 W/m^2). The flow type of fluids between heating and cooling Stirling engine array is also required to concern on designing a cascade system with Stirling engine array.

1. Introduction

Energy is the crucial part for the infrastructure and maintenance of society. With the increase amount of energy consumption, our quality of life has been improved significantly. However, nowadays the world energy consumption is highly dependent on fossil fuels, which supplied 81.2% of the world's energy consumption in 2013 according to the data of World Bank Group [1]. Using fossil fuels a lot is afflicting the environment, which is sacrificing our quality of life. Environmental pollutions and global warming are becoming serious problems, and it is urgent to find clean and renewable energy to substitute the fossil fuels.

Solar energy is a clean, sustainable, wide-distributed energy. However, solar energy has some disadvantages for its low flux density and large fluctuation due to daily and seasonal variations exacerbated by variations owing to weather. Concentrated solar power (CSP) technology has the ability to overcome these disadvantages and believed to be the future power generation technology [2]. There are 3 common commercial forms of CSP technologies, parabolic trough, dish Stirling and solar power tower, each with their advantages and disadvantages with different suitable working temperature zones. Combination of different collectors and/or cycles with different technologies may provide a new direction to achieve higher efficiency with lower cost for CSP.

Many researchers have done the work on the combination of different thermodynamic cycles for CSP. Lots of the work focused on integrated solar combined cycle (ISCC) with parabolic trough, where Rankine cycle is used as the bottom cycle. Li and Yang [3] proposed a novel two-stage ISCC system that could reach up to 30% of the net solar-to-electricity efficiency. In their research, the impact on the system overall efficiencies of how and where solar energy is input into ISCC system was investigated. Behar et al. [4] reviewed the R&D activities and published studies since the introduction of such a concept in the 1990s. One of the conclusions is that the higher the solar radiation intensity the better is the performance of the ISCCS than those of conventional CSP technologies. Gülen [5] used the exergy concept of the second law of thermodynamics to distil the complex optimisation of ISCCS to its bare essentials. After the exergy analysis, physics-based, user-friendly guidelines were provided to help direct studies involving heavy use of time consuming system models in a focused manner and evaluate the results critically to arrive at feasible ISCC designs. Shaaban [6] introduced a novel ISCC with steam and organic Rankine cycles. The ORC was used in order to intercool the compressed air and produce a net power from the received thermal energy. The proposed cycle performance was studied and optimised with different ORC working fluids. Alqahtani and Dalia [7] quantified the

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Nomenclature

$\dot{m}$	mass flow rate, kg/s
A	area, 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	heat capacity of Stirling engine working gas at constant pressure, J/(kg K)
c_v	heat capacity of Stirling engine working gas at constant volume, J/(kg K)
d	diameter, m
dep	depth, m
e	regeneration effectiveness of the Stirling engine
F_e	soiling factor of the trough collector
I_r	direct normal irradiance, W/m^2
K	incidence angle modifier of trough collector
k	specific heat ratio
n	number of collectors
n_1	number of columns of the Stirling engine array
n_2	number of rows of the Stirling engine array
n_g	amount of working gas in each engine, mol
n_{se}	number of Stirling engines in the Stirling engine array
P	power, W
p_c	exhaust pressure of turbine, Pa
p_s	main steam pressure of turbine, Pa
p_{amb}	ambient pressure, Pa
q''	heat flux, W/m^2
s_{se}	speed of Stirling engine, s^{-1}
T_H	highest temperature of expansion space, K
T_L	lowest temperature of compression space, K
T_R	regenerator temperature, K
T_s	main steam temperature of the turbine, K
i	isentropic; inlet
$insu$	insulating layer
p	parallel flow
pu	pump
s	stand-alone systems
se	stirling engine
T_{amb}	ambient temperature, K
$T_{s,d}$	designed mean steam temperature of turbine, K
U	overall heat transfer coefficient, $W/(m^2 K)$
v_{amb}	ambient wind speed, m/s
w	width, m
x	dryness fraction
y	extraction rate of steam turbine

Abbreviations

CSP	concentrated solar power
ISCC	integrated solar combined cycle
LFC	linear fresnel collector
ORC	organic Rankine cycle
PTC	parabolic trough collector
SRC	steam rankine cycle

Greek symbols

β	ratio of power of Stirling engines to the total output power of cascade system
δ	thickness, m
ε	emissivity
η_{diff}	efficiency difference of cascade system and stand-alone systems, $\eta_{cs} - \eta_s$
$\eta_{shading}$	shading factor
γ	intercept factor; compression ratio
λ	thermal conductivity, W/(m K)
ϕ	incidence angle
ρ	reflectivity
θ_{dc}	dish aperture angle (0° is horizontal, 90° is vertically down)

Subscripts

c	counterflow
cs	cascade system
dc	dish collector
de	deaerator
ge	generator
sea	Stirling engine array
tc	trough collector
x	Stirling engine in column x
1	first fluid (air)
2	second fluid (water)

economic and environmental benefits of an ISCC power plant relative to a stand-alone CSP with energy storage, and a natural gas-fired combined cycle plant. Results show that integrating the CSP into an ISCC reduces the LCOE of solar-generated electricity by 35–40% relative to a stand-alone CSP plant, and provides the additional benefit of dispatch ability. Manente [8] developed a 390 MWe three pressure level natural gas combined cycle to evaluate different integration schemes of ISCC. Both power boosting and fuel saving operation strategies were analysed in the search for the highest annual efficiency and solar share. Result shown that, compared to power boosting, the fuel saving strategy shows lower thermal efficiencies of the integrated solar combined cycle due to the efficiency drop of gas turbine at reduced loads. Rovira et al. [9] compared the annual performance and economic feasibility of ISCC using two solar concentrating technologies: parabolic trough collectors (PTC) and linear Fresnel collectors (LFC). Different configurations were considered and results shown that only evaporative configuration is the most suitable choice. Compared with traditional ISCC design, two new conceptual hybrid designs for ISCC with parabolic trough were represented by Turchi and Ma [10]. In the first design, gas turbine waste heat is supplied for both heat transfer fluid heating and feed water preheating. In the second design, gas turbine waste heat is supplied for a thermal energy storage system. Mukhopadhyay and Ghosh [11] presented a conceptual configuration of a solar power tower combined heat and power plant with a topping air Brayton cycle. The conventional gas turbine combustion chamber is replaced with a solar receiver. A simple downstream Rankine cycle with a heat recovery steam generator and a process heater have been considered for integration with the solar Brayton cycle. Li et al. [12] presented a novel cascade system using both steam Rankine cycle (SRC) and organic Rankine cycle (ORC). Screw expander is employed in the steam Rankine cycle for its good applicability in power conversion with steam-liquid mixture. The heat released by steam condensation is used to drive the ORC. Al-Sulaiman [13] compared the produced power of an SRC-ORC combined cycle with traditional SRC cycle. The SRC is driven by parabolic trough solar collectors, and the ORC cycle is driven by the condensation heat of the SRC. This combined cycle is a typical cascade utilisation of the solar energy, which uses the condensation heat of the top Rankine cycle to drive a bottom Rankine cycle. Bahari et al. [14] considered the optimisation of an integrated system using organic Rankine cycle to utilise