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Review

A brief review study of various thermodynamic cycles for high temperature power generation systems

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ABSTRACT

This paper presents a review of the previous studies and papers about various thermodynamic cycles working for high temperature power generation procedures, in these cycles the highest temperature is not lower than 700 K. Thermodynamic cycles that working for power generation are divided into two broad categories, thermodynamic cycle model study and working fluid analysis. Thermodynamic cycle contains the simple cycle model and the complex cycle model, emphasis has been given on the complex thermodynamic cycles due to their high thermal efficiencies. Working fluids used for high temperature thermodynamic cycles is a dense gas rather than a liquid. A suitable thermodynamic cycle is crucial for effectively power generation especially under the condition of high temperature. The main purpose is to find out the characteristics of various thermodynamic cycles when they are working in the high temperature region for power generation. As this study shows, combined cycles with both renewable and nonrenewable energies as the heat source can show good performance.

Contents

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Nomenclature

CCGT	combined cycle gas turbine
ChGT	chemical gas turbine system
DSG	Direct Steam Generation
EGT	Exhaust Gas Temperature
HIPPS	high performance power systems
HP	high pressure
HPT	high pressure turbine
HRSG	Heat Recovery Steam Generator
HTF	Heat Transfer Fluid
IGCC	Integrated Gasification Combined Cycle
IP	intermediate pressure
IPT	intermediate pressure turbine
ISCC	Integrated Solar Combined Cycle
LEC	levelized energy cost
LHV	Low Heating Value
LP	low pressure
LPT	low pressure turbine
MFE	micro-fuel element
MOBIS	Modular Optimal Balance Integral System
NLP	Non-Linear Mathematical Programming
OFC	Organic Flash Cycle
ORC	Organic Rankine Cycle
OSCA	Optimized Supercritical Cycle
PTC	Parabolic Trough Collector
RCG	Rankine Compression Gas Turbine
SCR	Solar Central Receiver
SD	Stirling Dish
SEGS	solar electric generating system
SOFC	solid oxide fuel cell
TE	Thermo-Electric
TIT	turbine inlet temperature
TIT1	turbine inlet temperature of first combustor

1. Introduction

As the depletion of non-renewable energy becomes more serious and people's awareness about the environmental pollution, utilizing this energy effectively as well as promoting the use of the renewable energy should be on the road. Since most fractions of these environmental pollutions are caused through power generation, focus should be on this area. High efficient thermodynamic cycles used for power generation especially under the high temperature conditions are needed. The thermodynamic cycles working for power generation have been studied for a long time for increasing the power generation efficiency.

According to Carnot cycle, the maximal efficiency η_c of the energy conversion process is defined as bellow:

$$\eta_c = 1 - T_c/T_h \tag{1}$$

where T_c is the minimal temperature and T_h is the maximum temperature of the cycle, respectively.

Eq. (1) clearly indicates that in a thermodynamic cycle, the higher the temperature at which heat is supplied, the higher the efficiency of the cycle. To use the energy efficiently, thermodynamic cycles working at high temperature should be considered.

Gas turbine cycle is widely used and still keeps continuing enhancing to be adopted in power generation due to the great availability of fuel resources, the significant reduction in capital costs and the integration with other simple cycles [1]. Furthermore, a small improvement could significantly impacts on its thermal efficiency under high temperature condition. And the operation conditions are much important for the gas turbine. Göktun and Yavuz [2] analyzed a high thermal efficiency Brayton cycle with an irreversible regeneration and an isothermal heat addition, the peak temperature of the isothermal heat addition process approaches approximated 1000 K. However, the regenerative technology is not always positive for thermodynamic cycle under high temperature condition. Such as the role of regeneration in chemical gas turbine (ChGT) system with high pressure ratios [3].

Steam turbine has mature development and a widely usage since it is firstly invented by Parsons [4] in 1884. The efficiency of the steam cycle can be improved by applying reheating technology or by reducing the irreversibility of the steam generator [5]. Reheating process in the steam cycle can increase the average heating temperature of the system and the efficiency of the expansion process in the steam turbine. In addition, the temperature of the steam cycle cannot be much high. Even with a special design dedicated for high temperature operation for turbines [6], the steam temperature is limited to below 923.15 K. For this reason, steam cycle is mostly acted as bottoming cycle. For reducing the heat loss, Kalina cycle uses a zeotropic mixture of ammonia and water as the working fluid which is proposed in early 1980s [7–9]. Since the different working fluids used in these two thermodynamic cycles, Kalina cycle is 10–20% more efficient than a Rankine cycle with the same boundary conditions as the bottoming cycle [10]. Smith et al. showed a Kalina cycle with a net plant efficiency of 58.8%, which is 2% higher than the best Rankine cycle system [11]. Sayed [12] gave a detailed analysis of the entropy generations for the Rankine and Kalina cycle. And the results showed that only 75.1% of the input exergy could be transmitted to the rest of the Rankine cycle, while that of the Kalina cycle is 85.1%. Jurgen [13] studied that Kalina cycle help to convert approximately 45% of the heat input of a direct-fired system to electricity and up to 52% for a combined-cycle plant in theory. These values will be about 35% and 44% for the steam cycle, respectively. However, as the same as steam cycle, the working temperature is limited by the working fluid. Therefore, how to improve the efficiency of steam bottoming cycle as well as Kalina bottoming cycle becomes the most challenge.

In recent years, combined cycles with various heat sources are being applied. Sarabchi and Polley [14] modeled and optimized a single-pressure combined cycle. Makansi pointed out that the basic arrangement especially fueled by natural gas, are becoming the dominant power generation system on a worldwide basis [15]. In addition to that, the solar-driven combined cycles which has been studied since the 90s was initially proposed by Luz Solar International [16]. Lior et al. [14,17] studied a solar-powered, fuel superheated Rankine cycle incorporating with a steam turbine. The low temperature steam of 375.15 K can be generated by solar energy, and then is superheated to be about 873.15 K in a fossil-fuel fired super-heater. However, these systems are utilized with much low efficiency.

For improving the application efficiency, various working fluids are studied. Feher [18] studied simple Rankine cycle and recuperated Brayton cycle when they are working at supercritical state. Cycle performance analysis, effect of component parameters, and working fluids selected have been done as the turbine inlet temperature of 810.93 K to 1144.26 K while the pressure drop ranges from 0 to 0.1. Resulting that with CO_2 as the working fluid and a nuclear reactor as the heat source, the supercritical cycle is potential for power generation under high temperature condition. The furnaces of the Malone engines manufactured between 1925 and 1927 were stoked with coal and coke [19,20]. Since various liquids