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Research Paper

The improved distribution method of negentropy and performance evaluation of CCPPs based on the structure theory of thermoeconomics

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HIGHLIGHTS

- An integrated and reasonable thermoeconomic model of CCPPs based on structure theory is built.
- The production and consumption of negentropy in each component of CCPPs are clearly analyzed.
- The distribution method of negentropy is improved according to quantitative relation in two cycles.
- An improved relative cost difference is proposed by introduction of non-energy weighting factor.
- Performance evaluation of CCPPs is conducted based on proposed thermoeconomic model.

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ABSTRACT

In order to evaluate the performance of components in the large gas-fired combined cycle power plant (CCPP), an improved thermoeconomic analysis method based on the structure theory of thermoeconomics is proposed. First, the fuel-product model is established; the productive structure and the distribution method of negentropy are modified. Negentropy produced and consumed in the gas turbine cycle is also considered. It is proved that the method is reasonable and practical. The exergy cost by the method is higher than that by the traditional method. Then, thermoeconomic model based on structure theory is built by using the improved distribution method of negentropy. Compared with matrix model of thermoeconomics, the accuracy and the effectiveness of the model are verified. The relative error is less than 3%, which is within the permissible range of engineering. Afterwards, relative cost difference and exergoeconomic factor are calculated. The improved relative cost difference is put forward through introduction of non-energy weighting factor. The results indicate that the heat recovery steam generator (HRSG) has a very great potential improvement. The investment on the steam turbine (ST) and the irreversibility of the combustion chamber (CC) should also be paid more attention, the decrease of which makes a great contribution to the decrease of thermoeconomic cost. It shows that the new evaluation index for components of CCPP is reasonable and will support the researches on thermoeconomic optimization of CCPPs.

1. Introduction

Compared with common coal-fired power stations, gas–steam CCPPs have high thermal efficiency, low pollutant emission, short construction period and good load adaptability advantages. These advantages just make up for the deficiency of the current thermal power plants. The CCPPs have higher thermal efficiency than the separate steam and gas turbine cycle power plants. The combined cycle power generation is one of the most promising directions in the future [1,2]. The optimization of power generation systems is one of the most important subjects in the field of energy engineering. Exergy analysis and thermoeconomic analysis based on the first and second thermodynamic laws are significant tools to analyze the energy systems. The main goal of energy analysis is to detect and evaluate the thermodynamic system quantitatively. It reveals the inefficient thermodynamic processes. On the other hand, the second law of thermodynamics deals with the quality of energy and determines the obtainable maximum amount of work from an energy resource [3].

There are many researchers studying on the CCPPs using various kinds of methods. Methods based on the first and second thermodynamic laws are widely used to evaluate, design and optimize the CCPPs [4–7]. Nag and Raha [8] made a thermodynamic analysis of a combined cycle power plant using pressurized circulating

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fluidized beds for partial gasification and combustion of coal. Chiesa and Macchi [9] conducted the thermodynamic analysis and showed that the efficiency of the CCPP higher than 61% could be achieved in the frame of current and available technology. Chen et al. [10] used the equivalent enthalpy drop method to make an economical analysis for a 600 MW supercritical power plant in two different extraction heating ways.

Thermodynamic analysis can only compute system efficiency and quantify the irreversible loss in the devices from the local perspective. Economic analysis can calculate the fuel cost, investment, operation and maintenance cost of the whole system from the global perspective. But it is unable to evaluate the formation and distribution of the cost in a subsystem or equipment. Thermodynamic analysis and economic analysis are complementary, which makes it possible to combine thermodynamics with economics [11–14]. Thermoeconomic analysis methods based on exergy are also called exergoeconomic analysis methods, which are constantly used. Barzegar Avval et al. [15] performed the exergy, exergoeconomic and exergoenvironmental analysis of a CCPP. The results showed that combustion chamber had the greatest exergy destruction and also had the greatest cost of exergy destruction in comparison with other components of the cycle. Ahmadi and Dincer [16] performed an exergoeconomic optimization of a 1000 MW light water reactor power generation system using a genetic algorithm. Xiong et al. [17] carried out a detailed thermoeconomic cost analysis of a 600 MWe Oxy-combustion pulverized-coal-fired power plant. Reddy et al. [18] conducted a comparative analysis for the two current technologies. The exergetic analysis showed that boiler was the main source of exergetic power loss in coal-fired supercritical thermal power plant and combustion chamber in the gas-fired CCPP. It is concluded that natural gas-fired CCPP was better from the viewpoints of thermal efficiency and exergy efficiency.

Many studies of coal-fired unit have been done based on structure theory of thermoeconomics, but less for the gas–steam combined cycle units. Especially, there are two problems that are not very clear for gas–steam combined cycle units. One is the distribution of negentropy produced by the system among components. The other is that there is not an appropriate performance evaluation index to conduct a crosswise comparison among components, and the old indexes are confirmed to be limited.

In this paper, thermoeconomic model of the CCPP is established based on the structure theory of thermoeconomics. Comparing with the traditional model, the productive structure is modified and the distribution method of negentropy is more reasonable. Thermoeconomic generation cost is obtained through the theoretical calculation of thermoeconomic model. The performance evaluation indicator is improved by introducing a weight coefficient to the traditional relative cost difference. Finally, a reasonable evaluation of the CCPP is performed based on the improved relative cost difference and exergoeconomic factor.

2. System description

The gas–steam combined power plant is gaining popularity in the municipal and industrial markets as a profitable way to generate both electrical power and mechanical horsepower. The gas turbine system consists of an air compressor (AC), a CC and a turbine. The gas is completely burned and expands through the gas turbine (GT). The expanded gas is led to an HRSG. The feed water is heated, evaporated and superheated at high pressure in the HRSG. After expansion in the high pressure cylinder (HPC) of steam turbine, the steam is re-superheated in the HRSG and conducted to the intermediate and low pressure cylinder (IPC, LPC). Finally, the expanded steam is condensed in the condenser (CND). The remaining heat is discharged to the environment by cooling water and a cooling tower. The mechanical work of the GT and the ST is converted into electricity in one single generator (GEN). Fig. 1 illustrates the detailed process of the proposed single-shaft combined cycle unit.

There are many different design alternatives for the CCPP due to the large quantity of design parameters that should be taken into consideration, such as the pressure level, the distribution of economizers, evaporators and superheaters in the HRSG, and the use of reheaters or preheaters [19,20]. In this paper, the typical 9FA single shaft gas–steam combined cycle generating unit is taken as the research object. The thermodynamic system diagram is shown in Fig. 1. The device models and parameters of design condition are as shown in Table 1.

In the following section, thermoeconomic analysis will be conducted based on the proposed system. The paper consists of four parts. First, the method and procedure of thermoeconomic model based on structure theory of thermoeconomics will be stated. Second, the exergy flows of the whole system and the distribution method of negentropy will be discussed in detail, which is the foundation of the calculation. Then the established model is verified through the matrix model of thermoeconomics from the aspects of unit thermoeconomic cost of product and efficiency. And the unit thermoeconomic costs under variable off-design condition are also provided. Finally, traditional performance evaluation indexes are performed and the improved relative cost difference is put forward, which is suitable for transverse comparison among all components. Performance evaluation of the proposed CCPP system is conducted, and the potential components that may contribute to high efficiency are pointed out.

As a consequence the structural theory is a general mathematical formalism either for thermoeconomic cost accounting and/or optimization methods, providing a common basis of comparison among the different thermoeconomic methodologies, which could be considered the standard formalism for thermoeconomics. Thermoeconomic cost accounting is the basis of modeling based on structure theory of thermoeconomics, which can be logically divided into two parts: (1) exergy cost analysis and (2) non-energy cost accounting. Thermoeconomic cost accounting for CCPP is presented in the next section.

3. Exergy cost analysis

Exergy cost analysis can be logically defined by the following procedures: (1) A physical structure of the plant is built first. (2) The fuel-product model of each device is defined depending on the functionality of the component in the physical structure, which will be converted into the productive structure. (3) The thermoeconomic model represented by a set of characteristic equations can be easily obtained using the productive structure.

3.1. Physical structure

The thermodynamic system diagram must be converted into a physical structure for more detailed thermoeconomic analysis. Individuals in the physical structure are defined as components. Several units/equipment could be aggregated into one subsystem; also one unit can be disaggregated into several individual components [21]. The physical structure could be complex or simple. Different aggregation (or disaggregation) levels generate different physical structures. More details in modeling a physical structure should provide better possibilities for analyzing the plant. However, the cost of computation increases obviously when aggregation level decreases. Therefore, there must be an optimum level of aggregation (i.e. level of detailed description in the physical structure) corresponding to the depth of analysis. The selected physical structure in this paper is presented in Fig. 2, which is very similar to the thermodynamic system diagram (depicted in Fig. 1).