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A new approach to determining the intermediate temperatures of endoreversible combined cycle power plant corresponding to maximum power

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ABSTRACT

Determining the optimal operating temperatures of power plants corresponding to maximum power is important for not only the analysis of cycle performance, but also the selection of appropriate working fluids and their pressures. This study develops a new and convenient approach to determining the intermediate operating temperatures of n-stage endoreversible combined cycle power plants comprising n (arbitrary number) Carnot heat engines corresponding to the twice maximized power output by using the entransy transfer efficiency as an auxiliary parameter. The new approach reveals that when the temperatures of the hot and cold reservoirs, the total thermal conductance as well as the stage number of the n-stage power plant are given, only two of these intermediate temperatures have fixed values, while the other ones are variable. It provides considerable flexibility for the designers to the selection of the optimal operating temperatures and appropriate working fluids. The procedures for determining all the possible values of these intermediate temperatures are demonstrated. Next, a practical optimization problem of a two-stage combined cycle power plant is taken as an example to illustrate the superiority of the newly proposed approach to the existing one. Finally, the physical meaning of entransy transfer efficiency, together with its limitation is discussed and a comparison between the entransy-based efficiency and exergy-based efficiency is presented.

1. Introduction

Improving the thermal performance of power plants has been regarded as one of the key issues in energy conservation. It is known that in all cycles between two heat reservoirs of different temperatures, the work output and the thermal efficiency are maximal when the cycles are reversible. However, the power output of a reversible cycle is zero since its operation time is infinitely long which is obviously meaningless for engineering applications. In order to obtain a certain amount of power, models of endoreversible cycles by considering the irreversibilities of finite-time heat transfer processes are proposed by Chambadal [1], Novikov [2], and Curzon–Ahlborn (C–A) [3] and developed by Andersen, Salamon and Berry [4–6]. This method of modeling and optimizing a real thermodynamic cycle was referred to as finite time thermodynamics (FTT), a branch of thermodynamics devoted to extend classical reversible thermodynamics to include more realistic processes. By now, this model has been widely used to analyze the performance of heat engines, heat pumps and refrigerators [7–9] with the main goal of ascertaining the performance bounds and optimal criteria of selecting thermodynamic parameters of heat devices with finite time cycles.

One of the endoreversible models that a number of researchers are interested in is the n-stage combined cycle power plant comprising n (arbitrary number) reversible Carnot heat engines, as shown in Fig. 1 [10]. It is a universal model from which the optimal performance concerning an arbitrary-stage endoreversible or reversible combined Carnot cycle system may be directly derived. Moreover, successful efforts have been made to use this model as a reference one to analyze irreversible combined cycle power plants by incorporating the most important irreversibilities into it [8,10–13].

Determining the intermediate operating temperatures of each reversible cycle of the n-stage combined cycle power plant (i.e., $T_{H,i}$ and $T_{L,i}$ in Fig. 1) corresponding to maximum power output is a major concern to engineers since they could select the appropriate working fluids and their operating pressures according to the optimization result. When the number of stage, n, is small ($n = 1$ or $n = 2$), there are only a few intermediate operating temperatures, and thus their values that correspond to maximum power

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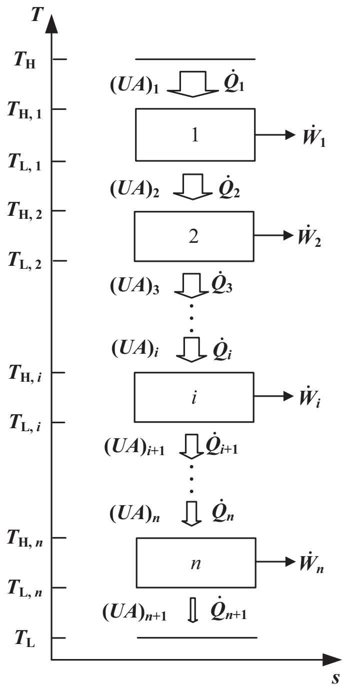

Fig. 1. An n-stage combined cycle power plant comprising n reversible Carnot heat engines, where each Carnot cycle in the system is connected through two heat exchangers and $(UA)_i$ is the thermal conductance of the ith heat exchanger, where U is the heat transfer coefficient and A is the heat transfer area. Only the first and the last heat engines are exposed to the hot (T_H) and cold (T_L) reservoirs, respectively [10].

can be readily obtained [14–16]. When the number of stage, n, is larger than two, however, the number of the intermediate temperatures that are unknown and need to be determined may be quite large.

By now, several optimal operating conditions for the n-stage combined cycle power plant have been reported. Bandyopadhyay et al. [10] have noted that all of the intermediate operating temperatures corresponding to the maximum power may be chosen arbitrarily, as long as the relation $\prod_{i=1}^{n}\frac{T_{L,i}}{T_{H,i}}=\sqrt{\frac{T_L}{T_H}}$ is satisfied. Furthermore, Bandyopadhyay et al. [10] and Bejan [16,17] have found that the power produced by an n-stage combined power plant can further be optimized for a given total thermal conductance ($UA=\sum_{i=1}^{n+1}(UA)_i=\text{constant}$) when UA is divided equally among all the heat exchangers, that is, $(UA)_i=UA/(n+1)$ (the corresponding power is referred to as twice maximized power output in this paper, as in Refs. [17,18]). Herein, it may raise a question: Is there any approach to determining the intermediate operating temperatures of an arbitrary-stage combined cycle power plant that corresponds to the twice maximized power output? Obviously, the relation $\prod_{i=1}^{n}\frac{T_{L,i}}{T_{H,i}}=\sqrt{\frac{T_L}{T_H}}$ alone cannot give a satisfactory answer of this question since it can only tell us the relation of the intermediate operating temperatures corresponding to the "once" maximized power output rather than the "twice" one. To the author's best knowledge, this question has not been addressed by other existing literature either.

The purpose of this paper is to propose a convenient approach to determining the intermediate operating temperatures of an arbitrary-stage combined cycle power plant corresponding to the twice maximized power output, and thereafter to show that when T_H, T_L, n and UA are given, only two of these intermediate temperatures have fixed values, while the other ones are variable, satisfying a general formula. This study will help designers to make a quicker judgment about the choice of working fluids and their operating pressures.

The plan of this paper is as follows. Considering that the entransy transfer efficiency serves as an auxiliary parameter for accomplishing the purpose intended, we start this paper in Section 2 with a discussion of this concept from the aspects of its origin, definition and application. In Section 3, we introduce the new approach and describe the procedures for finding all the possible optimal intermediate temperatures. In Section 4, a two-stage combined cycle power plant is taken as an example to illustrate the feasibility and superiority of the newly proposed approach. A discussion of the physical meaning of entransy transfer efficiency and a comparison between the entransy-based efficiency and exergy-based one are presented in Section 5. In Section 6, an attempt is made to derive the optimal intermediate temperatures based on entransy loss and entropy generation analysis. The paper concludes with a summary and an appendix. All the processes/cycles discussed are assumed to operate continuously under steady-state conditions.

2. Entransy transfer efficiency

2.1. Origin

The essence of efficiency, in general, is the ratio of the produced valuable resources to the consumed ones, reflecting how effectively the input is converted to the product. For instance, the heat-work conversion efficiency is defined as

$$\text{Heat-work conversion efficiency}=\frac{\text{Energy out in product}}{\text{Energy in}}=\frac{\dot{W}}{\dot{Q}_{in}}. \quad (1)$$

For a heat transfer process at steady-state, as shown in Fig. 2, however, if the product and consumable are quantified in the unit of heat (or heat flow), the heat transfer efficiency, quantitatively determined by the ratio of heat output to heat input, is always 100% because of the energy conservation law, that is,

$$\text{Heat transfer efficiency}=\frac{\text{Energy out in product}}{\text{Energy in}}=\frac{\dot{Q}_{out}}{\dot{Q}_{in}}\equiv 100\%, \quad (2)$$

which is meaningless to evaluate the performance of a heat transfer process.

Recently, from the analogy between heat conduction and electric conduction, Guo et al. [19,20] found that temperature, as the thermal potential, corresponds to the electrical potential, and Fourier's law corresponds to Ohm's law. Therefore, the thermal energy stored in an incompressible object should correspond to the electrical charge stored in a capacitor. However, there is no

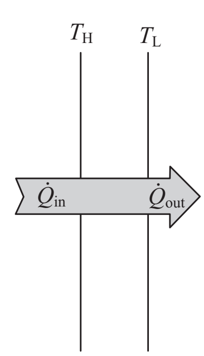

Fig. 2. Sketch of a heat transfer process.