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Efficiency improvement of thermal power plants through specific entropy generation

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ABSTRACT

Numerous studies have indicated that when neither the rate of heat input nor the power output in a thermal power plant is treated as a fixed parameter, minimizing the entropy generation does not lead to an improved thermal efficiency. This article presents a unified approach to resolve this issue by introducing *specific* entropy generation defined as the total entropy generation rate per unit flowrate of the fuel. A regenerative gas turbine and a combined cycle power plants are chosen for the purpose of discussion. It is found that the thermal efficiency inversely correlates with specific entropy generation, and minimization of specific entropy generation is identical to maximization of thermal efficiency. An illustrative example is presented to show how specific entropy generation can be applied to improve the efficiency of an integrated cycle. The results reveal that 85% of the inefficiencies of the combined cycle studied takes place in the gas turbine cycle. Recovering the thermal energy of the flue gases for both preheating the air and producing the steam within heat recovery steam generator yields 3.5 percentage points more efficiency than the case in which the heat of flue gases is only recovered for producing steam. With this modification, minimum specific entropy generation is dropped from 1489 to 1391 (J/K·mole fuel).

1. Introduction

Entropy-based analysis is used as a tool to identify inefficiencies, measured in terms of entropy generation or exergy destruction, in power generating systems. There has been arguments in the scientific literature whether minimizing the entropy generation may lead to a maximum thermal efficiency in a heat-power converting device. In 1975, Leff and Jones [1] investigated possibility of any relation between the thermal efficiency and entropy generation in an irreversible engine. They argued that unless the heat input to the engine or the heat rejected by the engine is fixed, an increase in the thermal efficiency of an irreversible heat engine would not necessarily lead to a decrease in its entropy generation.

In 1996, Bejan [2,3] presented models of power plants that would operate at maximum power while producing minimum entropy generation rate. The heat input to the heat engines examined by Bejan was explicitly assumed constant. Argued by Bejan was that to accurately determine the rate of total entropy generation associated with the operation of a power plant, one must also account for the entropy generation term due to the heat rejected by the engine to the surrounding environment. Salamon et al. [4] discussed that maximum power output and minimum entropy generation rate may become equivalent under certain design conditions.

Haseli [5,6] investigated the operation of various configurations of Brayton cycle at the condition of minimum entropy generation and found that for the case of fixed heat input, maximum thermal efficiency, maximum work output and minimum entropy generation are coincident. Further, for the case of fixed work output, minimization of entropy generation rate is identical to maximization of thermal efficiency. On the other hand, for an *endoreversible* power cycle experiencing only the external irreversibilities due to the heat transfer processes to and from the cycle, the thermal efficiency inversely correlates with entropy generation irrespective of whether heat input or power output is fixed [7]. Haseli [8] has also shown that minimization of entropy generation in irreversible standard thermodynamic cycles is neither equivalent to maximization of thermal efficiency, nor to maximizing the work output.

Cheng and Liang [9] investigated the entropy generation rate of a one-stream heat exchanger network (HEN) with the Carnot engines. They found that the minimum entropy generation rate corresponds to the maximum power output from the one-stream HEN when the heat capacity flow rate and the inlet temperature of the hot stream were fixed. Sun et al. [10] analyzed a reheat Rankine cycle and a single-stage steam extraction regenerative Rankine cycle by optimizing the operating conditions at varying steam mass flow rate, the combustion temperature and the flow rate of the flue gas. The results indicated that the minimum exergy destruction rate would lead to a maximum output

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Nomenclature

c_p	specific heat, J/mol·K
h	enthalpy, J/mol
H	enthalpy per mole of fuel, J/mol fuel
HV	heating value, J/mol
k	specific heat ratio
n	molar flowrate, mol/s
p	pressure, Pa
Q_L	rate of heat rejected per unit molar flowrate of fuel, J/mol fuel
R	universal gas constant, J/mol·K
s	specific entropy, J/mol·K
S	entropy per unit molar flowrate of fuel, J/K·mol fuel
SEG	specific entropy generation, J/K·mol fuel
T	temperature, K
TIT	turbine inlet temperature, K
W	power per unit molar flowrate of fuel, J/mol fuel
y	mole fraction

Greek letter

ε	heat exchanger effectiveness
η	efficiency
λ	stoichiometric coefficient

Subscripts

c	compressor
cc	combined cycle
com	combustor
g	combustion gases
t	turbine
th	thermal

power if the combustion temperature and heat capacity flow rate of the flue gas were fixed.

Feidt et al. [11] presented models of the irreversible Carnot engine with finite heat transfer areas and speed of the engine through the entropy ratio method of irreversibility and the method of entropy production rate. Their results showed that the maximum power output of the engine did not systematically correspond to the minimum entropy production rate. Li et al. [12] calculated the thermal efficiency, power output and the rate of entropy generation for an Organic Rankine Cycle. They concluded that minimizing the entropy generation rate did neither correspond to maximum thermal efficiency, nor to maximum power output. Zhou et al. [13] reports that the minimum entropy generation rate corresponds to the maximum output power in a closed Brayton cycle if the inlet conditions of the hot and cold streams are fixed.

Klein and Reindl [14] investigated minimum entropy generation rate for a refrigeration cycle using a vapor compression cycle model. They found that minimizing the entropy generation rate does not always result in the same design as maximizing the COP of the refrigeration cycle unless the refrigeration capacity is fixed. Cheng and Liang [15] analyzed a refrigeration cycle and reported that minimization of entropy generation could lead to a maximum coefficient of performance (COP) if the temperature of heat source is fixed.

It can be concluded from the above survey that a reduction in the entropy generation rate in an irreversible power cycle does not always lead to an increase in thermal efficiency unless either the rate of heat input or the net power output is kept constant. In practice, a power plant is designed and constructed to meet a certain power requirement. In this case (fixed power output), a design based on minimum entropy generation rate would lead to exactly a design that corresponds to maximum thermal efficiency. We will get back to this case latter in Section 4. However, if the power output is unknown and treated as a varying parameter, for instance, when investigating the feasibility of a new integrated system, minimization of entropy generation rate may not lead to a maximum thermal efficiency. This will be demonstrated in Section 4.

This article presents a unified approach to show how an entropy-based analysis should be performed to gain useful information for design purposes even when the rate of heat input or the power output is not a fixed parameter in thermal power plants. It is important to realize that the combustion of fuel is the major driver to operate a heat engine such as steam and gas turbine power plants. So, it is also appropriate to systematically account for the amount of fuel burnt when applying an entropy analysis. Conventionally, the entropy generation in a power cycle is calculated regardless of how much fuel is consumed. In contrast to the previous works on this subjects; e.g. [5,9,15], the present article will take into account the overall combustion reaction of fuel.

It is proposed to compute the rate of entropy generation per unit flowrate of fuel, which will be called *specific entropy generation* (SEG) throughout this article. As the gas turbine and combined cycle power plants are popular means of power generation, the specific entropy generation will be determined for a regenerative gas turbine cycle and a combined steam/gas turbine power plant. Both of these power cycles have received tremendous attention from the scientific community and many articles have been published on the performance modeling of these power generating systems.

For instance, Sánchez-Orgaz et al. [16] developed a model for a multi-step regenerative Brayton cycle with reheating and intercooling intermediate processes. They have also presented a multi-objective and multi-parametric optimization analysis for a recuperative multi-step solar-driven Brayton thermo-solar plant [17]. Cao et al. [18] investigated the optimum design and thermodynamic performance of a gas turbine and organic Rankine combined cycle. Polyzakis et al. [19] investigated various configurations of a gas turbine cycle combined with a steam power plant. Adams and Mac Dowell [20] presented a detailed model of a 420 MW combined cycle power plant integrated with an amine based carbon dioxide capture and storage.

Unlike past studies, this article does not intent to present a conventional thermodynamic analysis to determine the efficiency and power output. Rather, the objective is to show how a specific entropy generation analysis can be useful to enhance the overall thermal efficiency when neither the power output nor the rate of heat input is treated as a fixed parameter. Following the work of Bejan [2,3], the entropy generation due to the rejection of heat from the power plants will be accounted for in the calculation of the total entropy generation rate.

2. A regenerative gas turbine power cycle

A schematic of a regenerative gas turbine power cycle is depicted in Fig. 1. It consists of a compressor, a heat exchanger, a combustor, and a turbine. Air consisting of 21% oxygen and 79% nitrogen (mole basis) is supplied form the ambient. The combustion gases are assumed to consist of carbon dioxide, steam, oxygen and nitrogen. For simplicity of the analysis, the pressure drop on the path of the working fluid is neglected and all gaseous species are treated like ideal gases.

2.1. Thermodynamic analysis

The thermodynamic analysis will be performed per unit molar flowrate of the fuel assumed to be methane in this work. Within the combustor, methane is burnt in air according to the following reaction.