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Thermodynamic analysis of waste heat power generation system

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A R T I C L E I N F O

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A B S T R A C T

In the present work, a waste heat power generation system is analyzed based on the criteria with and without considering the heat/exergy loss to the environment. For the criteria without considering the heat/exergy loss to the environment, the first- and second-law efficiencies display different tendencies with the variations of some system parameters. When the heat/exergy loss to the environment is taken into consideration, the first and second law efficiencies display the same tendency. Thus, choosing the appropriate expressions for the performance criteria is crucial for the optimization design of the waste heat power generation system. It is found that there are two approaches to improving the system performance: one is to improve the heat/exergy input; the other is to enhance the heat-work conversion ability of the system. The former would deteriorate the environment if the heat-work conversion ability of the system remains unchanged; the latter could reduce the environmental impact but it's restricted by the heat/exergy input. Therefore, the optimal operation condition should be achieved at the trade-off between the heat/exergy input and the heat-work conversion ability of the system.

1. Introduction

Last decades witness the rapidly rising prices of coal, petroleum and other fossil fuels and severe environmental pollution. It is of great importance to deal with these two issues. Using energy sources efficiently is one of the most effective ways to reduce energy demand, meanwhile to lessen impact of the fossil fuels on the environment. Recently, the waste heat recovery technology in power plant has attracted a great deal of attention. Generally, the first law of thermodynamics is employed to analyze this thermodynamic system. However, the heat transfer and heat-work conversion processes are characterized as the irreversible processes. Therefore, the second law of thermodynamics must play the pivotal role in quantifying the irreversibilities and evaluating the system performance [1].

There are many criteria to assess the performance of thermal systems based on the first- and second-law of thermodynamics, but the expressions for them are usually perplexing and unclearly recognized. Lior and Zhang [2] clarified the definitions and usage of energy, exergy and second law efficiency, and pointed out that some errors caused by the differences between exergy and second law efficiency can be made if the equations and systems are not defined carefully. Bejan [3–6] conducted a systematic investigation on the applications of entropy generation in heat and mass transfer processes and devices, and introduced the dimensionless entropy generation number N_s to evaluate the performance of heat exchanger. Nag and De [7] applied the entropy generation minimization approach to the optimization design of a heat recovery steam generator generating saturated steam for a combined gas and steam power cycle. Reddy et al. [8] derived a general equation of the entropy generation for a waste heat recovery steam generator and investigated the effects of various non-dimensional operating parameters, such as heat capacity rate ratio, non-dimensional inlet gas temperature difference ratio, heat exchanger units etc., on entropy generation number. Casarosa et al. [9] developed a thermoeconomic optimization method for the design of the heat recovery steam generator, based on a combination of the thermodynamic and economic analyses, and found that the overall combined cycle efficiency was possible to reach 60% without modifying gas turbine characteristics. An organic Rankine cycle (ORC) system was analyzed by Wei et al. [10], it was found that the usage of exhaust heat should be maximized, the condenser should be cooled properly, and a proper nominal condition should be chosen in order to improve the system performance. Butcher and Reddy [11] investigated the influences of gas composition, specific heat and pinch point temperature on the performance of a waste heat recovery based power generation system, and found that the first- and second-law efficiencies are sensitive to gas composition.

Due to the increasingly adverse influence of greenhouse effect on human life, the study of reducing the environmental impact of energy industries has attracted a lot of attention in recent years. Meyer et al. [12] proposed an exergoenvironmental analysis to investigate the environmental impact associated with energy

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Nomenclature

a_i	constant
c_p	specific heat (J kg^{-1} K^{-1})
EXg	exergy destruction of the exhaust gas in the system (J)
EXg_E	total exergy supplied by the exhaust gas (J)
h	specific enthalpy (J kg^{-1})
m	mass flow rate (kg s^{-1})
N_s	entropy generation number
NTU	number of transfer units
$NTUS$	number of transfer units for superheater
$NTUB$	number of transfer units for evaporator
$NTUE$	number of transfer units for economizer
$NTUC$	number of transfer units for condenser
P	pressure (Pa)
P_o	inlet pressure of the exhaust gas (Pa)
Q	heat transfer rate (W)
R	gas constant (J kg^{-1} K^{-1})
s	specific entropy (J kg^{-1} K^{-1})
S_{gen}	entropy generation rate (W K^{-1})
SI	sustainability index
T	temperature (K)
T_o	ambient temperature (K)
V^*	non-dimensional gas velocity
W_{net}	net work output (W)
X_1	ratio of heat capacity rate of superheated steam to that of the exhaust gas
X_2	ratio of heat capacity rate of water to that of the exhaust gas
x	steam quality

Greeks

ΔP_g	pressure drop of gas (Pa)
ΔPT	pinch point temperature (K)
ε	effectiveness
η	efficiency
ξ	pressure drop coefficient

Subscripts

c	condensation
cw	cooling water
E	environment
g	gas
I	the first law
II	the second law
p	pump
sat	saturated
s	superheated steam
t	turbine
w	water

conversion systems at component level, and to optimize design of the systems for a lower overall environmental impact. A life cycle analysis (LCA) was conducted by Singh et al. [13] to compare different design schemes for an industrial ecosystem. Tonon et al. [14] presented a comprehensive analysis based on integration of several methods, including thermodynamic, economic and environmental performance, for energy conversion processes.

As mentioned above, a waste heat recovery steam generator had been analyzed in terms of entropy generation number in [8], but the system did not include the heat-work conversion process. The influences of gas composition, specific heat, pinch point temperature and gas inlet temperature on a waste heat power generation system had been investigated using second law analysis [11], but the impact of the system on the environment has not been explored. In this paper, the whole system called "waste heat power generation system", including the waste heat recovery system and the power generation system as shown in Fig. 1 are investigated. Specifically, based on the first law efficiency, second law efficiency and entropy generation, the influences of some operation parameters, such as the turbine exergy efficiency, pumping operation and so on, on the performance of a waste heat power generation system are analyzed. Since the performance criteria for thermal systems are not clearly recognized and the magnitude errors can be made if the expressions of performance criteria are not given carefully [2], the criteria for assessing the performance of the system are divided into two groups in the present work: one doesn't take into account of the heat/exergy loss to the environment; another does. The influences of various operating parameters, such as gas inlet temperature, pump output pressure, etc., on the performance criteria of the waste heat power generation system are investigated, and the results will be useful for the waste heat power generation system. There are two approaches available for improving performance of the waste heat power generation system: enhancing the heat-work conversion ability of the system and increasing the heat/exergy input. The comparison between the two approaches will help the design-makers to choose the most effective approach to improving the performance of the system.

2. Thermodynamic analysis

The waste heat power generation system discussed in the present work mainly consists of an economizer, an evaporator, a superheater, a steam turbine, a condenser and a pump. In this system, the heat recovery steam generator obtains thermal energy from the high temperature exhaust gas, and generates high temperature superheated steam to drive steam turbine to do work, the circulation is maintained by the pumping process; the sketch of this system is shown in Fig. 1. The typical temperature-entropy

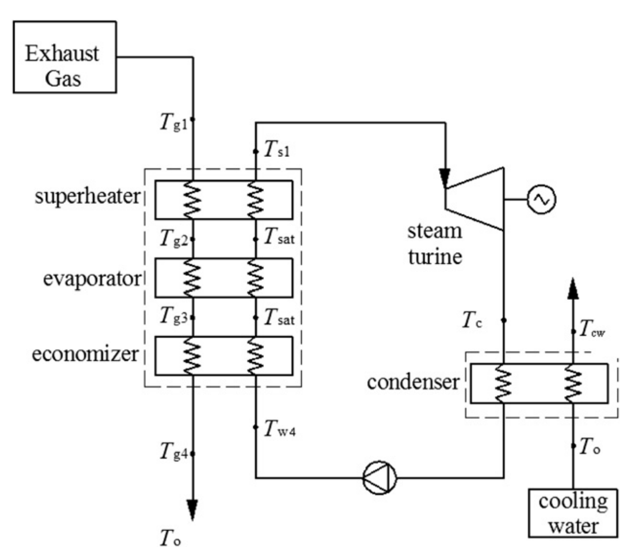

Fig. 1. Waste heat power generation system.