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Heat exchanger inventory cost optimization for power cycles with one feedwater heater

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ABSTRACT

Cost optimization of heat exchanger inventory in power cycles with one open feedwater heater is undertaken. In this regard, thermoeconomic analysis for an endoreversible power cycle with an open feedwater heater is shown. The scenarios of constant heat rejection and addition rates, power as well as rate of heat transfer in the open feedwater heater are studied. All cost functions displayed minima with respect to the high-side absolute temperature ratio (θ_1). In this case, the effect of the Carnot temperature ratio (Φ_1), absolute temperature ratio (ξ) and the phase-change absolute temperature ratio for the feedwater heater (Φ_2) are qualitatively the same. Furthermore, the constant heat addition scenario resulted in the lowest value of the cost function. For variation of all cost functions, the smaller the value of the phase-change absolute temperature ratio for the feedwater heater (Φ_2), lower the cost at the minima. As feedwater heater to hot end unit cost ratio decreases, the minimum total conductance required increases.

1. Introduction

Using feedwater heaters, also called regenerators, to enhance efficiency of steam power plants is a standard practice in industry and, therefore, thermoeconomic analysis of such systems is important. Feedwater heaters can either be open or closed type. When the heat is transferred from the steam (bled from the turbine) to the feedwater by mixing, it is considered an open type. The advantages offered include a higher efficiency of the power plant due to a rise in the average temperature of heat addition. Next, it helps to prevent boiler corrosion by providing an easy way to remove air that leaks into the condenser. Also, it lowers the volume flow in the final turbine stages. For further details, the work of Babcock & Wilcox [1] may be consulted along with textbooks on Thermodynamics such as Cengel and Boles [2].

Authors such as Bejan [3,4] addressed the issue of heat exchanger inventory allocation for different situations such as maximizing the efficiency. The Carnot model developed by Bejan [4] was used by Antar and Zubair [5] to study cost optimization of power plant heat exchanger inventory for a specified power output. The total inventory reached a minimum when the unit cost ratio attained unity. Sahin and Kodal [6] carried out thermoeconomic optimization of endoreversible heat engines using a new thermoeconomic optimization criterion i.e. power output per unit total cost. Analytical equations for optimum working fluid temperatures, specific power output, thermal efficiency and distribution of heat exchanger areas were determined. The effect of relative fuel cost was also discussed. This new criteria was later used by the authors for irreversible heat engines [7] as well. Using profit maximization as the objective function, exergoeconomic performance optimization of a finite-time irreversible Carnot engine was investigated by Chen et al. [8]. The authors derived relevant formulae concerning profit and efficiency for this purpose.

Bandyopadhyay et al. [9] studied combined cycle power plant cost optimization using irreversible Carnot-like heat engines. It was found that the yearly plant cost rose along with a decline in power output as the number of stages was increased. For off-design conditions in combined cycle gas turbine power plants, Rovira et al. [10] performed thermoeconomic optimization in heat recovery steam generators. Based on design conditions, negligible difference was found in the optimization results when compared to those obtained from usual thermoeconomic models except for the fact that, with the new model, a minor decrease was seen in the amortization cost and design efficiency. For combined cycle power plants, genetic algorithms have also been used for the purpose of thermoeconomic optimization [11–13]. Using the Second Law of Thermodynamics, Silveira and Tuna [14] presented a thermoeconomic functional analysis method. Four cogeneration systems were analyzed and the system consisting of a gas turbine with heat recovery steam generator only was found to have the lowest exergetic production cost. Al-Sulaiman et al. [15,16]

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Nomenclature

A	area (m^2)
F	non-dimensional cost function (–)
G	unit cost conductance ratio (–)
K	non-dimensional quantity defined by Eq. (15f) (–)
k_1	ratio of feedwater heater to condenser entropy change (–)
$\dot{m}$	mass flow rate (kg s^{-1})
$\dot{Q}$	rate of heat transfer (kW)
s	specific entropy (kJ kg^{-1} K^{-1})
T	absolute temperature (K)
U	overall heat transfer coefficient (kW m^{-2} K^{-1})

Greek

Γ	total cost ($)
γ	unit conductance cost ($kW^{-1} K)
Φ_1	Carnot temperature ratio (–)
Φ_2	phase-change absolute temperature ratio for the feedwater heater (–)
θ_1	high-side absolute temperature ratio (–)
θ_2	average preheating absolute temperature ratio (–)
ξ	absolute temperature ratio (–)

Subscripts

01	at condenser
02	at phase-change in feedwater heater
a	constant rate of work
b	constant rate of heat rejection from the condenser
C	reversible compartment
c	constant rate of heat addition in the boiler
d	constant rate of heat transfer in the open feedwater heater
H	hot end
L	cold end
min	minimum
OFH	open feedwater heater
tot	total

performed thermoeconomic optimization of three trigeneration systems using organic Rankine cycles. Formulations were presented and the systems examined which revealed that, from the three systems, the solar trigeneration system offered the best thermoeconomic performance. Abusoglu and Kanoglu [17] reviewed exergoeconomic optimization and analysis for combined heat and power systems. A comparison of the advantages and disadvantages regarding important thermoeconomic methodologies found in the literature were made.

Xiong et al. [18] performed thermoeconomic optimization of a 600 MWe pulverized-coal-fired power plant using oxy-combustion. A 10% increase in unit thermoeconomic product costs was seen due to the extra power utilization for the oxy-combustion system and another 10% due to its other related costs such as operation and maintenance, investment as well as interest. Bassily [19] performed cost optimization of commercial combined cycle power plants with triple-pressure reheating. It was determined that, for a 400 MW power plant, an annual saving of about $29.2 million could be obtained by optimizing the net revenue.

Rosen and Dincer [20] thermoeconomically examined an electrical generating station fueled by coal based on capital cost only. They emphasized that the reason for this is that the capital cost is often the most significant cost component and costs other than that are often proportional to it. Thus, qualitative agreement is expected. For the design and analysis of energy systems, Silveira et al. [21] presented a thermoeconomic optimization methodology using the exergetic production cost as the objective function. Depending on the energy system analyzed, the various costs included operational and capital cost for a given amount and type of exergy. Seyyedi et al. [22] provided a new approach for optimization of thermal power plants based on the exergoeconomic analysis and structural optimization method. Important advantages of this new method are its applicability to large complex thermal systems and rapid convergence. Considering various objective functions based on finite-time thermodynamics and thermoeconomics, Durmayaz et al. [23] presented an extensive review on optimization of thermal systems. The conclusion of the authors was that finite-time thermoeconomic analysis needed more work in fundamental theory development and applications as it was still in its early stages.

It was found through the literature review that, for the endoreversible case of a power cycle with one feedwater heater, cost optimization has not been considered for design and performance evaluation purpose. Therefore, this paper aims to develop the relevant endoreversible models and then perform thermoeconomic analysis of this system. The scenarios of constant heat addition and rejection rates, power as well as rate of heat transfer in the open feedwater heater will be studied.

2. Mathematical framework

Following the methodology of Bejan [4] and Antar and Zubair [5], the endoreversible form of the power cycle with one open feedwater heater is now considered. The schematic of system under consideration is shown in Fig. 1(a) while Fig. 1(b) shows its T-s diagram. The purpose of the current study is to determine the minimum of the total cost of conductance (UA) for the following scenarios: constant rate of heat addition, power, heat transfer in the preheater and heat rejection. The Heat Exchanger Inventory Cost Equation (HEICE) can be written in terms of heat exchanger unit cost parameters as [5]:

$$\Gamma = \gamma_H (UA)_H + \gamma_L (UA)_L + \gamma_{OFH} (UA)_{OFH} \tag{1}$$

where γ_H, γ_L, and γ_{OFH} are unit cost of conductance for the boiler, condenser and preheater, respectively, such that Γ has units of dollars. Next,

$$\dot{Q}_H = (UA)_H (T_H - T_{HC}) \tag{2}$$

$$\dot{Q}_L = (UA)_L (T_{01} - T_L) \tag{3}$$

$$\dot{Q}_{OFH} = (UA)_{OFH} (T_{02} - \overline{T}_{OFH}) \tag{4a}$$

where $\overline{T}_{OFH}$ is the average preheating temperature and is given by:

$$\overline{T}_{OFH} = T_{02} - \Delta T_{OFH,avg} \tag{4b}$$

where $\Delta T_{OFH,avg}$ is the average amount of preheating and considered as half of the total achieved. Putting Eqs. (2)–(4) in Eq. (1) results in

$$\Gamma = \gamma_H \frac{\dot{Q}_H}{T_H - T_{HC}} + \gamma_L \frac{\dot{Q}_L}{T_{01} - T_L} + \gamma_{OFH} \frac{\dot{Q}_{OFH}}{\Delta T_{OFH,avg}} \tag{5}$$

Dividing throughout by γ_H, we get

$$\frac{\Gamma}{\gamma_H} = \frac{\dot{Q}_H}{T_H - T_{HC}} + \frac{\gamma_L}{\gamma_H} \frac{\dot{Q}_L}{T_{01} - T_L} + \frac{\gamma_{OFH}}{\gamma_H} \frac{\dot{Q}_{OFH}}{\Delta T_{OFH,avg}} \tag{6}$$