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Research paper

Thermoeconomic considerations in the allocation of heat transfer inventory for irreversible power systems

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HIGHLIGHTS

- Thermoeconomic optimization of an irreversible power cycle is done.
- Use of an irreversibility parameter was replaced with exact expressions.
- At optimal unit cost ratio, unequal division of heat transfer conductance was seen.
- Efficiency is dependent on unit cost ratio in contrast to the endoreversible case.
- Model is applicable to power systems based on sub-critical cycles.

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ABSTRACT

In this paper, thermoeconomic optimization of irreversible power systems with finite thermal capacitances for design situation is performed. Investigation is made with respect to the case of specified power output where exact expressions are determined without the use of an internal irreversibility parameter. The use of an internal irreversibility multiplier can omit important details even though it provides insight into real system behavior. Compared to the endoreversible case, the optimum hot-to cold-end unit cost ratio does not result in equal division of heat exchanger conductances and shows variation in the cycle thermal efficiency despite a constant fluid temperature ratio. It is also noted that optimization of the non-dimensional cost function does not translate into optimization of the thermal efficiency.

1. Introduction

Reversible cycles provide an upper limit to the value of performance parameters, e.g. thermal efficiency, but do not give any idea regarding their true values for real systems. By taking the irreversibility of finite time heat transfer into account, Chambadal [1] and Novikov [2] and, afterwards, Curzon and Ahlborn [3] extended the reversible Carnot cycle to the internally reversible (endoreversible) Carnot cycle, which resulted in limits closer to real heat engines. Finite time and finite size constraints on the performance of endoreversible as well as irreversible power systems were considered in many thermoeconomic optimization studies such as Bejan [4–6], Cheng et al. [7], Salah El-Din [8], Antar and Zubair [9], Agnew et al. [10], Bandyopadhyay et al. [11] and Rovira et al. [12], using various objective functions, e.g. optimized power output, minimized power generation cost and total heat exchanger area allocation.

In particular, Antar and Zubair [9] studied minimizing the cost of heat exchanger inventory in design situation, based on the Carnot model developed by Bejan [5], for the case of specified power output in single-stage endoreversible power systems. This was done by deriving a dimensionless Heat Exchanger Inventory Cost Equation (HEICE). Qureshi et al. [13] continued upon the work of Antar and Zubair [9] by using the same method for thermoeconomic optimization of an endoreversible power cycle with one open feedwater heater. They performed cost optimization for cases such as specified power output as well as rate of heat rejection and addition. The two variables that had a significant minimum with respect to the HEICEs were: the ratio between the hot-side fluid temperature to the hot-side reservoir temperature and the cold-to hot-side fluid temperature ratio. Compared to the work of Antar and Zubair [9], some dissimilarities in behavior were found e.g. the non-symmetric distribution of heat exchanger inventory with respect to the unit cost

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Nomenclature

A	area (m^2)
$\dot{C}_{\min}$	minimum value of the thermal capacitance rate ($kW\ K^{-1}$)
F	non-dimensional cost ratio for specified power output (–)
G	unit cost conductance ratio (–)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
$\dot{Q}$	heat transfer rate (kW)
S	non-dimensional entropy generation (–)
$\dot{S}_{gen}$	entropy generation rate ($kW\ K^{-1}$)
T	absolute temperature (K)
U	overall heat transfer coefficient ($kW\ m^{-2}\ K^{-1}$)
$\dot{W}_C$	rate of work done (kW)

Greek symbols

α	heat exchanger inventory on cold-side ($kW\ K^{-1}$)
β	heat exchanger inventory on hot-side ($kW\ K^{-1}$)
γ	unit conductance cost ($\$\ kW^{-1}\ K$)
Γ	total cost ($)
ε	heat exchanger effectiveness (–)
ε'	modified conductance $\left(=\frac{1}{\varepsilon}\ln\left(\frac{1}{1-\varepsilon}\right)\right)$ (–)
η	cycle thermal efficiency (–)
θ	high-side absolute temperature ratio defined by Eq. (16a) (–)
ϕ	irreversibility parameter (–)
Φ	fluid absolute temperature ratio defined by Eq. (16b) (–)
ξ	absolute temperature ratio defined by Eq. (16c) (–)

Subscripts

h	hot side
ER	endoreversible
H	hot end
IR	irreversible
in	entering
l	low side
L	cold end
min	minimum
mp	maximum power
out	exiting
tot	total
w	working fluid

ratio. An extensive review on thermal system optimization based on finite-time thermodynamics and thermoeconomics, which considered different objective functions was provided by Durmayaz et al. [14]. It was concluded that, at the moment, finite-time thermoeconomic analysis was in its early stages and that further work in fundamental theory development and applications was required. Manesh and Amidpour [15] performed a multi-objective thermoeconomic optimization of a multi-stage flash desalination plant with a nuclear power reactor using evolutionary algorithms. They explained that evolutionary algorithms are powerful tools and can be used to achieve better solutions. Usón and Valero [16] compared three thermoeconomic methodologies aimed at improving the operation of energy intensive systems. A conventional pulverized coal-fired power plant consisting of 3 units of 350 MW each was used as a case study. It was reported that only the method of quantitative causality analysis quantified the effects of all variables. Xiong et al. [17] optimized the operation of a 300 MW coal-fired power plant using the structure theory of thermoeconomics. Total annual and investment costs reductions of 2.5% and 3.5%, respectively, were achieved. Ding et al. [18] provided a unified description for finite time exergoeconomic performance for six endoreversible heat engine cycles. The cycle consisted of two, constant thermal-capacity, heating branches instead of the usual one. The authors aimed to find the compromised optimization between profit and efficiency. Pramanick and Das [19] did an interesting study on heat exchanger area allocation modeling for a generalized irreversible heat engine. They used a power law model for the external heat transfers instead of a linear one. While they found that this had an effect on the optimal heat exchanger allocation for maximum power output, they still concluded that the linear model is also capable of capturing the important aspects of a real power plant.

Irreversibilities in a power system involve: a) heat transfer across finite temperature differences, b) heat leaks, and c) the internal dissipation of the working fluid. Internal dissipation is related to inefficiencies in the pumping process and irreversibility due to expansion (in the turbine). Characterization of the internal irreversibility is often done using an irreversibility parameter (ϕ). As the working fluid goes through the two isothermal processes, this parameter measures the ratio of their entropy changes. The entropy inequality for internally irreversible cycles is written as an equality using this parameter such that:

$$\frac{\dot{Q}_L}{T_{l,w}} = \phi\frac{\dot{Q}_H}{T_{h,w}} \tag{1}$$

The efficiency would then be given by:

$$\eta_{mp} = 1 - \phi\frac{T_{l,w}}{T_{h,w}} \tag{2}$$

Generally, ϕ is a complicated function of the system operating variables and, therefore, may only be assumed constant in some cases. It follows that assuming a constant value of the irreversibility parameter would, in general, provide an averaged effect. Despite this, it has been used in many papers as it was mathematically simpler to incorporate and provided adequate insight into the behavior of system parameters [20]. Based on the above, it can be understood that the averaging effect of the irreversibility parameter may result in behavioral losses in some important variables. Therefore, the best method of measuring the internal dissipation effect would be to derive the exact mathematical expressions and then plot for the appropriate ranges.

The objective of the current work is to re-derive the cost equations developed by Antar and Zubair [9] for the irreversible power cycle design case and perform thermoeconomic optimization of (single-stage) power cycles without the use of an irreversibility parameter by developing exact equations. Furthermore, this will remove and demonstrate any losses in visualization of behavior that may occur because of the averaged effect of the irreversibility parameter.

2. Mathematical framework

Following on from the work of Bejan [5] and Antar and Zubair [9], irreversible cycles are considered for power systems. Fig. 1