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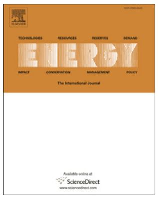

Analytical thermal efficiency of medium-low temperature organic Rankine cycles derived from entropy-generation analysis

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ABSTRACT

Conventionally, we need complete and accurate property diagrams or equations of state of the working fluid to calculate the thermal efficiency of ORCs (organic Rankine cycles). In this paper, we develop by entropy-generation analysis several analytical expressions for the thermal efficiency of ORCs. These analytical formulas are functions of several dimensionless variables, enabling fast and accurate calculations without recourse to thermodynamic diagrams or equations of state. The entropy-generation analysis clarifies the thermodynamic mechanism behind the effect of superheat in the evaporator on the thermal efficiency. Among the derived dimensionless variables, cT_3/r (T_3 is the evaporating temperature, r is the heat of evaporation at the evaporating temperature, and c is the average heat capacity of the saturated liquid) reflects the influence of the critical temperature on the thermal efficiency and can serve as an indicator of evaluating working fluids in the same group: thermal efficiency generally decreases with cT_3/r for the working fluids in the same category.

1. Introduction

Recently, applied researchers have been increasingly interested in applying ORCs (organic Rankine cycles) to the generation of power from a broad range of low-grade heat sources, such as medium-low temperature waste heat [1–3], geothermal energy [4–6], solar-thermal energy [7–9], biomass heat energy [10–12], and ocean thermal energy [13–15]. The outstanding characteristics of ORCs are technologically applicable [16].

The thermal efficiency of medium-low temperature ORCs is low; therefore, a great challenge lies in the reduction of costs. An economically-feasible ORC system depends on the selection of a working fluid, the design and the operating features of the system. A large number of studies have examined the performance of working fluids by screening a pre-compiled list of some available candidates [17–20]. The sets of candidates, however, are usually incomplete because the vast number of fluids could be used in ORCs. Thus, this approach may reduce the opportunities to identify novel and optimum working fluids for a given application. On the other hand, some researchers opt for computer-aided molecular design methods to optimize the selection or design of working fluids [21–23]. This computer-aided optimization method is very attractive, but it requires a robust optimization algorithm and a pre-specified database of molecules [16].

It is a great challenge to achieve optimum design and operation of ORC systems because they involve a complex set of influencing factors. For instance, the ORCs design problem requires an optimum decision on some discrete variables (e.g., heat exchanger types and the number of integrated cycles) and some continuous variables (e.g., thermal efficiency and equipment sizes) [16,24–27]. Efficient operation of ORC systems must properly deal with variations in a group of operating conditions: the flow rate and the temperature of the heat source, efficiency of the pump and the turbine, variation of heat transfer coefficients in the heat exchangers, etc. To conclude, a systematic approach to optimum design and control requires accurate system models and can lead to a serious computational challenge.

The computational challenge of modeling ORC systems is closely related to the computation of the thermal efficiency of the ORC. Thermal efficiency is also an important index for evaluating the performance of working fluids. Thermal efficiency is generally calculated by enthalpy balance equations in conjunction with complete and accurate property diagrams or equations of state.

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Nomenclature

c	specific heat, kJ/(kg K)
h	specific enthalpy, kJ/kg
k	specific heat ratio, dimensionless
P	pressure, kPa
q	heat per unit mass, kJ/kg
r	heat of evaporation
s	specific entropy, kJ/(kg K)
s_{gen}	entropy generation, kJ/(kg K)
T	temperature, K
w	work per unit mass, kJ/kg
η	efficiency, dimensionless

Subscripts

1, 2, …	state points
C	carnot
cr	critical point
h	high-temperature side
i	the ith state point
in	input
l	low-temperature side
out	output
p	constant pressure
s	isentropic process
t	turbine

Only the first law of thermodynamics is explicitly used by this method. The second law of thermodynamics is implicitly taken into account by using the experimentally validated property charts of real working fluids [28,29]. The conventional approach could bring about some trouble obtaining experimentally validated property diagrams (or equations of state). The difficulty will be insuperable if complete experimental data is unavailable. Moreover, this approach can be computationally intensive and complicated if highly accurate equations of state are involved. In this context, accurate analytical equations for thermal efficiency, which have explicit mathematical forms with only few input parameters, will be very desirable. Liu et al. derived an analytical expression for the thermal efficiency of ORCs using near-isentropic fluids by an entropy relation and the Watson equation [30]. Since the Watson equation is not exact [31], exact theoretical formulas suitable for all fluids are still unavailable.

The purpose of this work is to develop a set of accurate theoretical expressions for the thermal efficiency of medium-low temperature ORCs by explicitly applying the second law of thermodynamics. These new exact formulas are accurate, precise, and applicable in a general sense because few assumptions are used in the second-law analysis. Second-law analysis often uses the concept of exergy and calculates the exergy efficiency of ORCs [14,19,32–35]. This approach can identify irreversibility and potential energy saving components in thermodynamic systems [36,37], but it still relies on a complete property chart or equations of states for the working fluid. And exergy-based analysis cannot provide analytical equations for the thermal efficiency. Instead, we used the approach proposed by Alefeld [28], whereby entropy generations in key components are determined. Using this method, Alefeld derived several analytical expressions for the COP (coefficient of performance) of refrigerators and heat pumps. Our derivation is similar to his analysis but has more rigorous mathematical basis. We will demonstrate that the thermal efficiency of ORCs depends majorly upon several dimensionless variables, representing the effects of the condensing and the evaporating temperatures and the thermodynamic features of the working fluid. Our second-law analysis leads to a global entropy-generation analysis, which can quantify irreversible losses associated with the thermodynamic features of the working fluid. More importantly, these theoretical expressions provide a sound but easy-use basis for simulation, optimum design, and working-fluid selection of ORC systems.

This paper is organized as follows. Section 2 presents the theoretical developments of the analytical equations for the thermal efficiency of ORCs, while Section 3 gives some results of the new expressions with the purpose of validation. Section 4 discusses some features of the explicit expressions and draws some general insights into the thermodynamic performance of working fluids. Finally, Section 5 closes the paper by some conclusions.

2. Theoretical developments

2.1. Fundamental equations

As illustrated in Figs. 1 and 2, a working fluid is first pumped to an evaporator, whereby it is heated by an external heat source and experiences a liquid–vapor phase transition. The heat source can be low- or medium-temperature solar and geothermal energy. Next, the vapor from the evaporator drives a turbine to produce mechanical work. Then, the exhausted vapor enters a condenser, in which the vapor is cooled by an external cooling fluid and undergoes a condensing process. Finally, the condensed liquid is pumped into the evaporator again to repeat the cycle.

An ORC involves two heat transfer processes between the working fluid and external heat-carrier fluids. In second-law analysis, the most important temperature should be entropic average (i.e., thermodynamic average) temperatures, defined by

$$\frac{1}{T_{\mathrm{m}}}=\frac{1}{q}\int_{1}^{2}\frac{c_p dT}{T} \tag{1a}$$

or

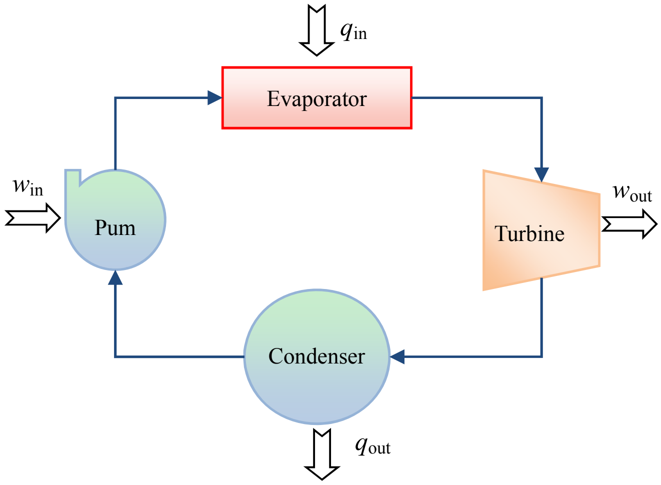

Fig. 1. Schematic layout of a simple organic Rankine cycle (ORC).