Research Paper

Reconstruction procedure of the thermodynamic cycle of organic Rankine cycles (ORC) and selection of the most appropriate working fluid

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HIGHLIGHTS

- An ORC modeling based on equivalent temperatures is described.
- A reconstruction method of the thermodynamic cycle is presented.
- The selection procedure of organic fluids based on various criteria is discussed.
- A case study is presented for various source temperatures.

ARTICLE INFO

ABSTRACT

Organic Rankine cycles (ORC) are part of heat recovery technologies, which allow thermal wastes to be converted into a mechanical power. These systems are suitable for various applications characterized by a large range of source and sink temperatures. Nonetheless, the selection of the organic working fluid is essential during ORC design processes; they have a major impact on the overall engine performance. Several works have been intending to develop appropriate methodologies to determine the optimal working fluid. Recently, an optimization approach independent of the organic fluid, has been proposed in the open literature, where optimal operating conditions are expressed in terms of equivalent temperatures and overall heat transfer surface areas. However, at the end, the primitive variables under which the real system must operate, should be determined. Within this framework, for a given working fluid, this paper presents a reconstruction method of a traditional thermodynamic cycle that allows actual thermodynamic variables (pressures, temperatures, mass flow rates) to be calculated. Furthermore, a methodology is also proposed for selecting the most appropriate organic working fluid, subjected to environmental and practical engineering design criteria. To emphasize the potential of the proposed approach, the entire procedure is then applied to a particular case study.

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1. Introduction

Organic Rankine cycles (ORC) permit low- to high-grade thermal energy to be partially converted into useful work (e.g. electricity). Therefore, their potential use appears very promising for various applications. Among others, it includes the conversion of solar energy into electricity and the valorization of thermal wastes coming from industrial and automotive sources as well as the regasification process of liquefied natural gas [1–7]. However, their possible integration to complex structures, such as co- and tri-generation [8,9], ejectors [10], heat pumps [11] and energy storage tanks [12,13], is also under investigation. The performance of such a technology is highly sensitive to the available thermal potentials of the sources. Hence, for each condition, several configurations of ORCs may present benefits as well as technical drawbacks [1,4]. For instance, it is possible to increase efficiency by using recuperative and/or regenerative ORCs while cascade, multi-evaporation and trilateral ORCs can permit a temperature glide of the secondary fluid to be closely followed when finite sources are considered [1]. Moreover, the selection of the organic fluid strongly affects the ORC performance. Hence, pure working fluids are generally examined and the use of zeotropic mixtures that are characterized by a non-isothermal phase change seems to be of great interest [1]. Moreover, the working fluid can eventually be at a supercritical state in transcritical cycles [1].

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Numerous organic fluids have been considered as potential candidates for the ORC technology and thus, have been examined in the open literature. For instance, Bao and Zhao [14], Chen et al. [15], and Quoilin et al. [4] have performed exhaustive reviews on the subject while other studies are specific to particular applications; from high [16] to low temperatures [17–22], and to zeotropic mixtures [23–25]. Systematic procedures have been developed to select the optimal working fluid [26,27]. In turn, another interesting approach has been proposed by Neveu et al. [28]. Since the previous works are based on methods that evaluate the performance of the thermodynamic cycle for each working fluid, Neveu et al. [28] developed an optimization method, independent of the working fluid. Applied to infinite sources, they presented a model based on both economic considerations and the use of limited information, principally the temperatures of the sources. This approach then allows the optimal operating conditions, as function of equivalent temperatures and overall heat transfer surface areas, to be obtained for all kind of working fluids. They applied their method to estimate the optimal pressures and temperatures of a Rankine cycle (i.e., using water) for concentrated solar power applications. To this aim, from optimal operating conditions they also developed a cycle reconstruction procedure to determine the primitive thermodynamic variables such as the working pressure, temperature, etc.

It must be pointed out that the reconstruction procedure is derived from the optimal equivalent temperature and arbitrary values of pinch points, which are not necessarily evaluated during the optimization. It is clear that, in order to retrieve the optimal value of the overall heat transfer surface areas, the values of pinch points must be manually tuned; nevertheless, this approach could be cumbersome. To overcome this issue, this paper discusses the methodology proposed by Neveu et al. [28] and an automatic ORC reconstruction procedure that relies on equivalent temperatures, and the products of overall heat transfer coefficients and heat transfer surface areas. Subsequently, based on the optimization results, a method for selecting the most appropriate working fluid is presented. For cases of low-temperature ORCs, the procedure is applied to several source temperatures and their impact on the selection of the working fluid is emphasized.

2. Thermodynamic analysis of the ORC model based on equivalent temperatures

Fig. 1a shows the configuration of a basic ORC for two infinite sources. It is composed of two heat exchangers (an evaporator and a condenser) operating at high and low temperatures, a pump and an expander. At the evaporator, a thermal source heats the working fluid at the highest system pressure. Mechanical work is then generated by the working fluid at the expander, where it undergoes a substantial pressure decrease. Heat removal is carried out in a low-pressure condenser where the thermal energy is transferred to a cold sink. The thermodynamic cycle is achieved by increasing the pressure of the working fluid up to the value prevailing in the evaporator. To securely operate both the pump and the expander in conventional ORC systems, some degrees of superheating and subcooling of the working fluid are mandatory; i.e. state C at the outlet of the evaporator and state A at the inlet of the condenser. The Mollier diagram of this cycle, for a dry organic fluid characterized by a positive slope of the saturation vapor curve, is shown in Fig. 1b. Note that the internal irreversibility in both the pump and the expander have been explicitly introduced in this diagram.

The classical thermodynamic approach is usually performed by applying energy, entropy and/or exergy balance equations to the individual components or to the whole system. Thus, the thermodynamic states (A-B-C-D in Fig. 1b) for a given organic fluid (i.e. the working fluid) are determined and the overall performance is estimated. Furthermore, the design of the heat exchangers and the use of more realistic (semi-empirical) models for the mechanical components can also be taken into consideration [29]. It is obvious that the implementation of this method for selecting the optimal working fluid necessitates to repeat the same procedure for each potential fluid. To overcome this inconvenient, Neveu et al. [28] have proposed an alternative approach based on the reformulation of the conservation equations by using the equivalent temperature ($\tilde{T}$), also known as the exergy equivalent temperature [30], defined as: