Simultaneous heat integration and techno-economic optimization of Organic Rankine Cycle (ORC) for multiple waste heat stream recovery

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In the past decades, the Organic Rankine Cycle (ORC) has become a promising technology for low and medium temperature energy utilization. In refineries, there are usually multiple waste heat streams to be recovered. From a safety and controllability perspective, using an intermediate (hot water) to recover waste heat before releasing heat to the ORC system is more favorable than direct integration. The mass flowrate of the intermediate hot water stream determines the amount of waste heat recovered and the final hot water temperature affects the thermal efficiency of ORC. Both, in turn, exert great influence on the power output. Therefore, the hot water mass flowrate is a critical decision variable for the optimal design of the system. This study develops a model for techno-economic optimization of an ORC with simultaneous heat recovery and capital cost optimization. The ORC is modeled using rigorous thermodynamics with the concept of state points. The task of waste heat recovery using the hot water intermediate is modeled using the Duran-Grossmann model for simultaneous heat integration and process optimization. The combined model determines the optimal design of an ORC that recovers multiple waste heat streams in a large scale background process using an intermediate heat transfer stream. In particular, the model determines the optimal heat recovery approach temperature (HRAT), the utility load of the background process, and the optimal operating conditions of the ORC simultaneously. The effectiveness of this method is demonstrated with a case study that uses a refinery as the background process. Sensitivity of the optimal solution to the parameters (electricity price, utility cost) is quantified in this paper.

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1. Introduction

In recent decades, as energy prices fluctuate and environmental pollution become more severe, efficient energy utilization has received widespread attention. In particular, the Organic Rankine Cycle (ORC) has become a promising technology for waste heat recovery due to its simplicity, feasibility, and reliability [1]. The ORC converts low-temperature heat into power and can be applied to many fields as solar thermal energy [2], geothermal energy [3], engine waste heat [4], biomass [5], and industrial waste heat [6]. Recently, Yari et al. [7] compared the trilateral Rankine cycle, Kalina cycle and organic Rankine cycle from the viewpoint of thermodynamic and exergeoconomics. They found that ORC is the most advantageous among the three options from the point of economics.

Parametric optimization and exergetic analyses were performed for both subcritical ORC and supercritical ORC by Yagh et al. [8]. Deethayat et al. [9] proposed a dimensionless term, Figure of Merit (FOM), to investigate the performance of ORC system for low temperature waste heat recovery with mixture working fluids.

For waste heat recovery in an industrial process, there are usually multiple waste heat streams. The design of an appropriate ORC will depend on the properties of the background process (i.e. waste heat streams). The decision of which streams to recover and what order to recover them exerts a large influence on the ORC system performance. Desai et al. [10] proposed a methodology for integration and optimization of an ORC considering the background process. Utilizing pinch technology, the operating conditions of the ORC are determined manually and the heat exchanger network is derived with a heuristic method. Based on this work, Chen et al. [11] proposed a two-step method to optimize the ORC and synthesize the heat exchanger network. In the first step, a stand-alone heat exchanger network is synthesized to minimize the hot utility.
In the second step, they incorporate the ORC into the heat surplus zone below the pinch point and maximize the power output. However, their work only samples ORC design parameters (e.g. evaporation temperature) at several specified values. Moreover, rigorous thermodynamic models for the ORC were not incorporated.

It is also important to consider the trade-off in capital cost and operating cost while designing an ORC for the purpose of recovering multiple waste heat streams. Li et al. [12] optimized a two-stage serial ORC system to maximize the ratio of net power output to total thermal conductance. Alternatively, Yang and Yeh [13] maximized the ratio of net power output to total heat exchanger area of an ORC for ocean thermal energy conversion. Yari et al. [7] performed exergo-economic optimization of an ORC to minimize specific investment cost. However, these works only consider heat exchanger costs; they do not consider the capital cost of the turbine, pump, and condenser. More detailed economic models are desirable to get a reliable measure of the ORC’s benefit.

In this paper, multiple waste heat streams are recovered by an intermediate hot water stream (for safety and practicality considerations). The hot water can be regarded as a cold stream in the heat exchanger network and as the heat source in ORC system. Along with the Duran-Grossmann model for heat integration, the model proposed in this paper includes rigorous thermodynamic models of the ORC and equipment cost correlations. This model can help engineers customize an economically optimal ORC to a background process, by considering heat integration and ORC design optimization simultaneously.

2. Problem definition

There are huge amounts of waste heat in the chemical and oil refining industries. So customizing an ORC to a waste heat redundant process is very attractive for industry in order to save cold utility and generate power. From the view of safety, control, and operability, using an intermediate hot water stream to transfer waste heat to the working fluid may be more practical. The ORC system analyzed in this work is represented in Fig. 1. The hot water stream enters the background process to recover waste heat; this is represented by the left hand side of Fig. 1, with the composite curves (CC) given by the lower left graphic describing the heat exchange occurring within the box outlined in the upper left. This hot water stream then releases the recovered heat to the organic working fluid in an ORC system, also represented by the T-S diagram in the lower right graphic of Fig. 1. The mass flowrate of hot water exerts great influence on the utility load of the heat exchanger network, the amount of waste heat recovered, the pump work consumed by the hot water pump, and the temperature of hot water at the outlet of the heat exchanger network. The hot water outlet temperature and its heat exchange behavior in the ORC in turn affects the ORC system thermal efficiency. The capital cost of ORC components interacts strongly with the operating conditions.
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