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Optimization of Organic Rankine Cycle Involving Operating Conditions and Work Fluids and Heat Integration

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In order to reduce the waste heat emission and environmental impact of industrial processes, Organic Rankine Cycle (ORC) is gradually used for energy recovery. ORC is regarded as the most promising measure for converting low-grade heat into electricity, but commercial applications are still limited due to the high investments and poor economic returns. However, the simultaneous optimization of ORC and Heat Integration can improve system economy. This work proposes a techno-economic optimization model involving the area estimate of heat exchanger based on vertical heat transfer for optimization of ORC and Heat Integration. This model determines the selection of working fluids, the optimal operating parameters of ORC including temperatures, pressures, and flowrate of working fluids. Both of the supercritical and subcritical conditions can be considered in this model. To solve this optimization problem, a bi-level optimization approach is developed, where the outer level uses Genetic Algorithm to identify the promising working fluids and optimize the temperatures and pressures of ORC, and the inner level is an NLP model to find the optimal flowrate of ORC and the vertical matches of streams by minimizing total annual cost. The results represent the necessity of simultaneous optimization of Organic Rankine Cycle and Heat Integration.

1. Introduction

Organic Rankine cycle (ORC) has attracted much attention because of its ability in recovering low-grade heat. It has the advantage of simplicity, feasibility, and reliability (Bao and Zhao, 2013), and can be applied to solar energy, biomass, geothermal energy, and industrial waste heat. However, commercial applications are still limited because of the high investments, poor electricity generation, and a long payback period. This contradiction between investment and revenue can be relieved through the optimization of ORC and Heat Integration for background processes.

Optimization and integration of ORC and background processes remain a challenging task. There is a large amount of candidate working fluids, the design of ORC structure has many different forms, and operating conditions including the temperature levels, pressure levels, and flow rates need to be decided to improve overall performance (Linke et al., 2015). In recent papers, Bendig et al. (2014) presented a methodology for the identification of suitable working fluids and ORCs, using Genetic Algorithm (GA) for the multi-objective optimization of suitable ORCs with available heat sources and MILP for Heat Integration. Yu et al. (2017) adopted the Duran-Grossmann model for simultaneous Heat Integration and ORC optimization, and this model determined the optimal heat recovery approach temperature, the utility load of the background process, and the optimal operating conditions of the ORC simultaneously. Kermani et al. (2018) proposed a bi-level optimization methodology for ORC integration including structural features such as turbine-bleeding, reheating, and trans-critical cycles. The outer level used GA to determine the working fluid and its operating conditions, and the inner level applies a sequential solution strategy to select the ORC architecture and equipment sizes using a MILP model. Castelli et al. (2019) adopted the evolutionary algorithm PGS-COM to determine the most promising working fluid and optimize ORC variables for the maximum exergy efficiency, then used the method of Elsido et al. (2019) based on the stage-wise superstructure to synthesize HEN and ORC.

The previous papers often applied multi-level optimization strategies to identify optimal working fluids and operating conditions. In the level for the optimization of ORC operating conditions, most papers ignored the cost

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of heat exchanger area, adopting the maximum power output or minimum total annual cost excluding area cost as the objective, because it is difficult to estimate area while the temperatures or flowrates of ORC streams are variables. The decision variables can be further improved in terms of economy by considering the area estimate. This work proposes a techno-economic optimization model involving the area estimate of heat exchanger based on vertical heat transfer of pinch technology for simultaneous optimization of ORC and Heat Integration. The working fluids, the optimal operating conditions of ORC including temperature levels, pressure levels and flowrate of working fluids can be determined in this model.

2. Method description

An optimization strategy for ORC design and Heat Integration is proposed in this section.

2.1 ORC structure

The ORC system consists of an evaporator, condenser, turbine, and pump. It can be classified into two groups according to the level of turbine inlet pressure of different working fluids, including supercritical ORCs and subcritical ORCs. These are both considered in this work.
The subcritical ORCs and supercritical ORCs can be generally represented in temperature versus entropy diagram for dry fluids as shown in Figures 1 and 2.

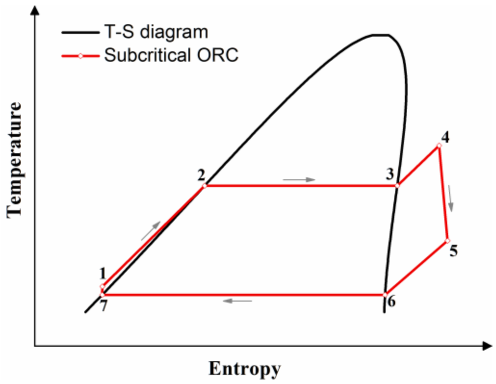

Figure 1: T-S diagram of subcritical ORC

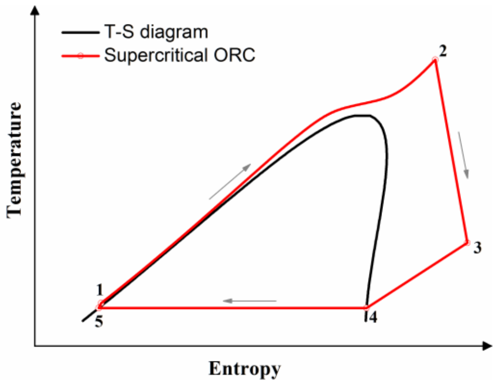

Figure 2: T-S diagram of supercritical ORC

In Figures 1 and 2, it can be observed that the thermal streams do not have fixed heat capacities in the evaporator or condenser. The operating conditions of streams in condenser often are the subcritical pressures and temperatures, which can be divided into two sub-streams including precooling stream (point 5 to 6) and condensing stream (point 6 to 7) in Figure 1. For the streams in the evaporator, there are two situations including subcritical evaporation and supercritical evaporation. For the subcritical condition, the stream in the evaporator can be divided into three-piece streams including preheating stream (point 1 to 2), evaporating stream (point 2 to 3), and superheating stream (point 3 to 4). For the supercritical condition, the piece-wise linearization can be used to divide the supercritical cold stream into multiply segments, as shown in Figure 3.

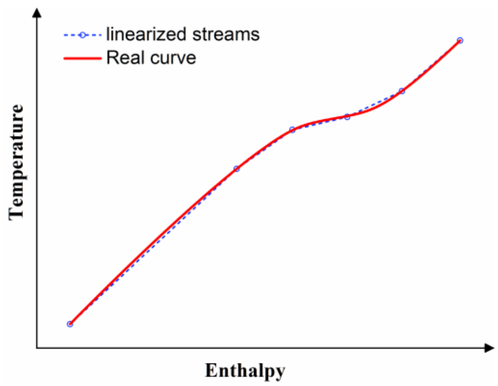

Figure 3: The piece-wise linearization for supercritical cold streams in the evaporator

2.2 Proposed optimization strategy

The proposed strategy is based on a bi-level procedure for ORC optimization and Heat Integration. Figure 4 illustrates the block-flow diagram of the proposed strategy. In the outer level, GA is applied to optimize the working fluids, evaporation pressure level (*Peva*), condensation pressure level (*Pcon*), and the degree of superheat (*Tsup*), and the related thermodynamic properties of the ORC streams, such as the temperatures, enthalpies, heat capacities, and power output of turbine are calculated with REFPROP v9.1 (Lemmon et al., 2013), for both working fluids. In the inner level, the NLP model is used to estimate area based on Pinch Technology and optimize total annual cost (TAC). The decision variables of this level are the flow rate of the working fluid and hot and cold utilities.

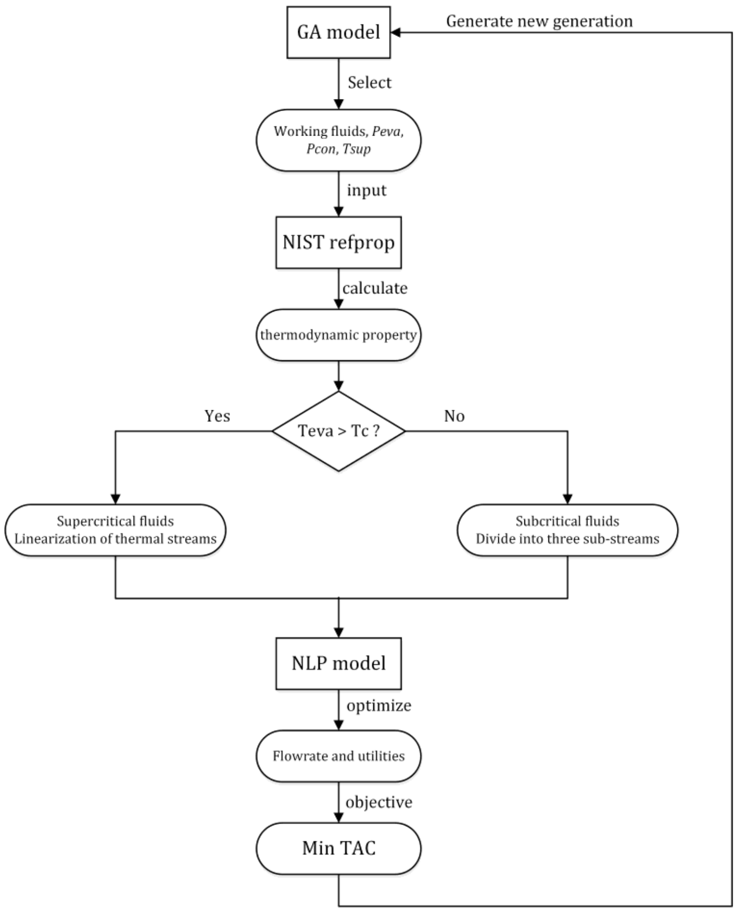

Figure 4: The block-flow diagram of the proposed strategy

2.3 Genetic algorithm

To avoid the equation of state with the high nonlinear and non-convex relationships due to the optimization of ORC pressures and temperatures, GA is used in outer-level optimization to select operating conditions of ORC. The thermodynamic properties can be calculated from REFPROP. The GA approach is a stochastic optimization method which involves searching randomly from solutions that imitate the biological processes of superiority, inferiority, and evolution of natural selection. First, create a set of many random method variables representing the genome, and after calculation, the genes/decision variables of the two individuals can be combined and mutated. The algorithm keeps the individuals that behave well in terms of the objectives. The algorithm is repeated until one of the convergence criteria is reached. These convergence criteria are the following:

- (a) the maximum number of 300 generations is reached.
- (b) the time limit of 5 h is reached.
- (c) the best individual does not change in 50 successive generations.

2.4 NLP model

The NLP model deals with the dynamic Composite Curve including the process streams, utility steams and ORC streams of which the flowrates of utilities and ORC are variable. The goal of this model is that estimate the heat exchanger area, optimize the TAC, and determine the flowrate of ORC streams and utilities.
Area estimation based on vertical heat transfer is the key to this model. Composite Curves（Smith, 2005）containing all hot and cold streams are represented in Figure 5 and generate multiply enthalpy intervals. When the stream conditions are all fixed, the Hot and Cold Composite Curves can be easily constructed. However, in this model, the variable flow rate leads to the change of Composite Curves and enthalpy intervals.

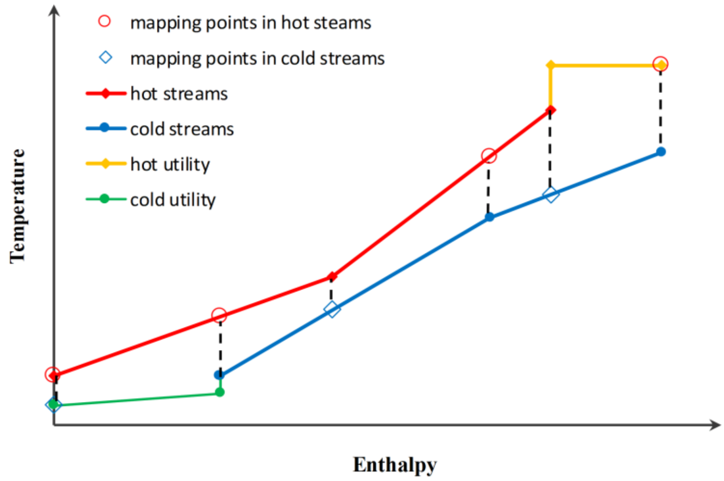

Figure 5: Composite Curves and enthalpy intervals

In the Hot and Cold Composite Curves, Th_n indicates all inlet and outlet temperatures of hot streams, the related enthalpy values (H_h_n) can be calculated by Eq(1). Similarly, Tc_m indicates all inlet and outlet temperatures of cold streams, the related enthalpy values (H_c_m) can be calculated by Eq(2).

$$H\_h_n = \sum_{i \in I} F_i Cp_i [\max\{0, Th_n - TOUT_i\} - \max\{0, Th_n - TIN_i\}] \quad \forall\, n \in N \tag{1}$$

$$H\_c_m = \sum_{j \in J} F_j Cp_j \left[\max\left\{0, Tc_m - TIN_j\right\} - \max\left\{0, Tc_m - TOUT_j\right\}\right] \quad \forall\, m \in M \tag{2}$$

where F_i and F_j represent the flow rate of the hot and cold streams, Cp_i and Cp_j are heat capacities of the hot and cold streams, TIN_i and TIN_j are the inlet temperatures of the hot and cold streams, $TOUT_i$ and $TOUT_j$ are the outlet temperatures of the hot and cold streams.
The temperatures of mapping points with the same enthalpy value can be calculated and generate enthalpy intervals between the Hot and Cold Composite Curves. The area of each enthalpy interval (A_s) can be calculated by Eq(3).

$$A_s = \frac{H_{s+1} - H_s}{U\left(\frac{dt_{s+1} - dt_s}{\ln \frac{dt_{s+1}}{dt_s}}\right)} \quad \forall s \in S \tag{3}$$

where s indicates the enthalpy interval, H_s is the enthalpy value of the enthalpy interval, dt_s is the temperature difference of the enthalpy interval, and U is the overall heat transfer coefficient.

2.5 Objective function

The objective function of this model is the minimum TAC including the capital cost ($COST_{cap}$) and the operating cost ($COST_{op}$), minus sale from the electricity generation of the ORC ($SALE_{el}$).

$$\min\ TAC = COST_{cap} + COST_{op} - SALE_{el} \tag{4}$$

where $COST_{cap}$ involves the area cost ($COST_{area}$), turbine cost ($COST_{tur}$) pump cost ($COST_{pump}$).

$$COST_{cap} = COST_{area} + COST_{tur} + COST_{pump} \tag{5}$$

TAC can be presented by Eq(6).

$$TAC = CCR\left(\sum_{s\in S} C_A A_s + C_{tur}W_{tur} + C_{pump}W_{pump}\right) + C_{CU}qcu + C_{HU}qhu - h_{op}p_{el}(W_{tur} - W_{pump}) \tag{6}$$

where CCR is annualization capital factor, C_A is the unitary area cost, C_{tur} and C_{pump} are the unitary cost of the turbine and pump, W_{tur} is the power output of the turbine, W_{pump} is the power requirement of the pump, C_{CU} and C_{HU} are the unitary cost of the cold and hot utilities. qcu and qhu are the cold and hot utilities, h_{op} is the annual operating time, p_{el} is the unitary selling price for electricity.

3. Case study and results

This case consists of two hot and two cold streams, along with one hot and one cold utility. The information of streams is listed in Table 1, and Table 2 represents the economic parameters for this case. The pressure levels, the temperature levels, the flow rate, and the working fluid need to be determined in this case. The isentropic efficiencies of the turbine and pump are 0.8 and 0.7. The minimum approach temperature difference is specified as 5 ℃. The candidates of working fluids include pentane, benzene, hexane, butane, and toluene.
The optimal results of each working fluid are listed in Table 3, in which hexane presents the minimum economic result. Selecting hexane as the working fluid of ORC, the optimal evaporation pressure level and condensation pressure level are 209.50 kPa and 30.71 kPa. The related TAC is 6.094 M$/y, which is 17.1 % lower than that of stand-alone Heat Integration without ORC.

Table 1: Data of process streams

Stream	*TIN* (℃)	*TOUT* (℃)	*FCp* (kW/℃)
HOT 1	187	77	300
HOT 2	127	27	500
COLD 1	147	217	600
COLD 2	47	117	200
HU	300	280	
CU	15	30	

Table 2: Economic parameters for the case

parameters			
CCR (y^{-1})	0.34	C_{CU} ($/kW·y)	10.1952
h (kW/m^2·℃)	0.5	C_{HU} ($/kW·y)	192.096
C_A ($/m^2)	360	h_{op} (h/y)	7,000
C_{tur} ($/kW)	300	p_{el} ($/kW·h)	0.10
C_{pump} ($/kW)	70		

Table 3: Optimization results for different working fluids

Results	Only Heat Integration	Pentane	Benzene	Hexane	Butane	Toluene
Mass flow rate (kg/s)	/	73.21	63.90	75.65	87.95	68.11
Evaporation pressure (kPa)	/	562.54	128.49	209.50	1270.61	57.38
Condensation pressure (kPa)	/	97.69	19.79	30.71	328.36	6.244
The degree of superheat (℃)	/	0	29.45	0.01	0	0
Net power (kW)	/	3,718.8	3,612.7	3,711.1	3,737.3	3,628.1
Hot utility (kW)	31,499.9	31,499.9	31,499.9	31,499.9	31,499.9	31,499.9
Cold utility (kW)	58,499.8	54,799.0	54,896.1	54,805.6	54,785.4	54,881.3
Total exchanger area (m^2)	5,747.4	13,877.9	13,483.6	13,884.9	14,380.7	13,551.0
Operating cost (M$/y)	6.647	6.610	6.611	6.610	6.610	6.611
Capital cost (M$/y)	0.703	2.088	2.020	2.082	2.167	2.029
Power sale (M$/y)	0	-2.603	-2.529	-2.598	-2.616	-2.540
TAC (M$/y)	7.351	6.095	6.102	6.094	6.161	6.100

4. Conclusions

This work proposes a techno-economic optimization model involving the area estimate of heat exchanger based on vertical heat transfer for optimization of ORC and Heat Integration. This model determines the selection of working fluids, the optimal operating parameters of ORC including temperatures, pressures, and flowrate of working fluids. A bi-level optimization approach is proposed, where the outer level uses GA to identify the promising working fluids and optimize the temperatures and pressures of ORC, and the inner level is an NLP model to estimate area and optimize flow rate of ORC and utilities by minimizing total annual cost. The case study shows the effectiveness of this model, the optimal result is 17.1 % of TAC lower than only Heat Integration without ORC.

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