CHEMICAL ENGINEERING TRANSACTIONS

VOL. 103, 2023

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Panos Seferlis, Yee Van Fan, Athanasios Papadopoulos

ISBN 979-12-81206-02-1; **ISSN** 2283-9216

DOI: 10.3303/CET23103024

Synthesis of Work-integrated Heat Exchanger Networks Coupled with Organic Rankine Cycles

Yongjian Huang, Yu Zhuang*, Lei Zhang, Jian Du

Frontiers Science Center for Smart Materials Oriented Chemical Engineering, Institute of Chemical Process Systems Engineering, School of Chemical Engineering, Dalian University of Technology, Dalian 116024, China
zhuangyu@dlut.edu.cn

Energy integration has been a research hotspot for decades, especially in the field of high energy consumption, like the chemical industry, and many methods for energy integration of process systems have been developed, such as heat exchange network synthesis and work-heat exchange network synthesis. There is still a considerable amount of medium and low-temperature waste heat that has not been effectively utilized in actual industrial production. In response to this problem, studies for the integration of the Organic Rankine Cycle (ORC) and process have been carried out. However, the relevant studies mostly focus on the coupling of ORC and heat exchange network for the recovery of waste heat and do not consider the effect of work production/consumption of the process streams, which neglects the influence of work-heat interaction on the coupling of ORC and work-integrated heat exchange network. This paper optimizes the integration of ORC and process stream with pressure/temperature change and designs a work-integrated heat exchange network. A two-layer genetic algorithm (GA) optimization strategy is proposed to determine the synthesis of heat exchange networks. The outer layer is to optimize the configurations of ORC, and the inner layer is to use an extended Duran-Grossmann model to determine the minimum utility consumption and the inlet temperature of the pressure-change sub-streams with the minimum exergy consumption as the objective function. Finally, the work-integrated heat exchange synthesis coupled with ORC is realized by an example study.

1. Introduction

As a significant issue in process systems engineering, energy integration has attracted scholars to conduct research and make important contributions to reducing consumption in industrial processes. Methodologies such as Heat Exchange Network Synthesis (HENS) and Work and Heat Network Synthesis (WHENS) have been proposed and developed. There are two main ways to design and optimize the heat exchange network, thermodynamic analysis and mathematical programming. The Pinch Analysis Method proposed by Linnhoff and Hindmarsh (1983) can effectively find out the limit of the heat recovery of the process. Yee et al. (1990) proposed a stage-wise superstructure method to realize the simultaneous synthesis of HEN, which can obtain a network with the lowest cost. When the problem extends to Work-Heat integration, these two methods have also been applied. Wechsung et al. (2011) proposed a method for heat exchange network synthesis where pressure levels of process streams could be changed to enhance heat utilization and increase energy efficiency. Yu et al. (2018) developed an MINLP model based on the Duran-Grossmann model to optimize the thermodynamic path for pressure-change streams with minimal exergy and next figure out the HEN synthesis problem. Lautaro et al. (2022) proposed a model for simultaneous synthesis of WHENs that regard pressure-change streams as low-pressure hot streams as well as high-pressure cold streams in different stages of the WHEN and reduce computational complexity. In order to recover the low-temperature heat that is rarely recovered by process, Organic Rankine Cycle (ORC) is applied to recover the waste heat. Desai and Bandyopadhyay (2009) proposed a method to integrate an ORC with a background process using pinch analysis techniques and pointed out that the shape of the grand composite curve determines the potential shaft-work output of the ORC. Chen et al. (2014) established a mathematical model for a synthesis problem of HEN integrated with ORC to recover waste heat from the process based on a stage-wise superstructure and proposed a two-step solution procedure to solve the MINLP model. Dong et al. (2020) proposed a two-level optimization method for optimal ORC design

Paper Received: 27 May 2023; Revised: 30 July 2023; Accepted: 30 August 2023
Please cite this article as: Huang Y., Zhuang Y., Zhang L., Du J., 2023, Synthesis of Work-integrated Heat Exchanger Networks Coupled with Organic Rankine Cycles, Chemical Engineering Transactions, 103, 139-144 DOI:10.3303/CET23103024

and heat integration, where the outer level optimizes the ORC operating conditions and the inner level is an NLP model that includes heat exchanger area calculation and objective function of the total annual cost. Chen et al. (2020) presented a multi-objective MINLP model to handle the trade-off between the equivalent thermal resistance and the TAC by limiting the ORC to absorb heat below the pinch point of alone-HEN. Supaluck et al. (2022) proposed a mathematical programming model for the synthesis of ORC-integrated heat exchanger networks. Their model realizes simultaneous optimization of the ORC and the HEN with both structural and parameter optimization of the ORC considered.

However, few studies consider the integration of ORC and processes with pressure changing, which may lead to unexpected gains since the addition of pressure-change heat inevitably increases the integration space and enables ORC to play a more effective role in heat recovery. In this work, a model is presented to realize the integration of ORC and a process that contains compressors and expanders, where the Duran-Grossmann model is used to obtain the minimal utility consumptions, and the heat exchange network problem is tackled after determining the configuration of the ORC.

2. Problem statement

Given the supply and target temperatures (TIN, TOUT) and heat capacity flowrates (F) for a set of cold and hot process streams, certain of which require to be compressed or expanded (PIN, POUT). Organic Rankine Cycle (ORC) is used to get more heat recovery, and a basic structure for ORC is adopted, which contains a turbine and a pump, condensers, and evaporators. The boiling and cooling processes of ORC are considered isobaric. For a certain working fluid, evaporation, and condensation pressures are two manipulating variables to optimize the ORC operating conditions as well as the mass fraction when the binary mixed working fluid is used. The mass flow is taken as a fixed value. The design goal is to get a network with minimal exergy consumption under the requirements of reaching the target temperature and pressure. In addition, a few assumptions are considered to focus on the heat integration: 1) the heat loss and pressure drop during heat exchange are ignored; 2) The polytropic efficiency of the compressors and expanders are constants; 3) Isothermal mixing is considered for pressure-change streams.

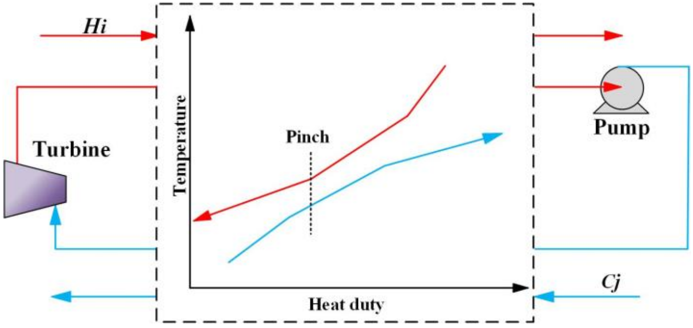

Figure 1: Heat integration for process streams and ORC

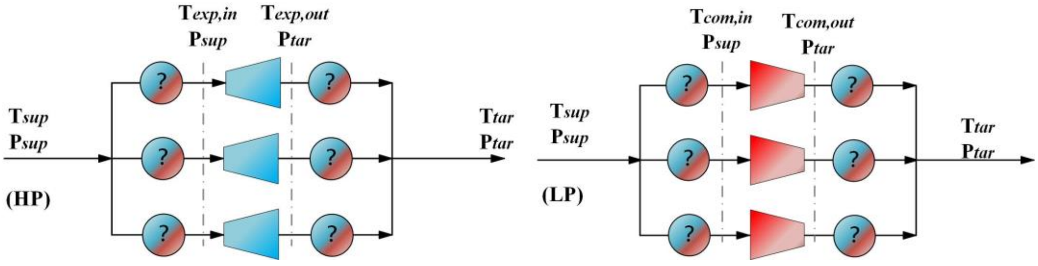

Figure 2: Superstructure for the potential thermodynamic path of the high-pressure (a) and low-pressure (b) streams

3. Model formulation

To solve the synthesis problem, a two-step strategy is designed to realize the optimization of ORC operating conditions and pressure operation conditions for process streams and then solve the heat exchange network synthesis problem. In the first step, Genetic Algorithm (GA) is used to optimize the evaporation pressure and condensation pressure of the ORC as well as the three branch streams of the high-pressure (HP) streams and low-pressure (LP) streams, whose superstructures are shown in Figure 2. As the chart shows, the flowrate, as well as the starting temperature of the compressors/expanders for each branch stream, are variables and need to be optimized.

3.1 Model to determine ORC operating conditions and conditions for pressure-change streams

In this stage, the task is to obtain the optimal operation parameters of ORC and optimal thermodynamic paths for pressure-change streams. A two-layer genetic algorithm optimization procedure is designed to solve the problem, where the outer layer optimizes ORC, and the inner layer optimizes inlet temperature and heat capacity flowrates of the branch pressure-change streams. Take these parameters (evaporation pressure, condensation pressure, mass fraction, starting temperature of compressors and expanders) as the optimization variables and encode them into genes for evolution. Thermodynamic properties of the state point (as shown in Figure 3) for organic fluids are calculated based on the given pressure and state (vapor fraction or others), which can be calculated by REFPROP 9.0. Exergy consumption is taken as the optimization objective and the component of fitness in the genetic algorithm.

3.1.1 Model for ORC

As shown in Figure 3, the ORC is decomposed into several sub-processes, pressurization (1-2), constant pressure heating (2-5), constant pressure cooling (6-1), expansion (5-6), overheating is a given value in this work. So, the working fluid can be classified as cold and hot streams in different stages of the cycle, as shown in Table 1. To obtain a solution for the model, a small temperature difference (0.5 K) is assumed for the isothermal phase transition of the pure organic working fluid, and the calculation for each sub-stream of the ORC is given by Eq(1).

Table 1: Sub-streams of the ORC

Sub-stream	Point of ORC	Inlet temperature	Outlet temperature	Heat duty
ORCC1	2—>3	t_2	t_3	$m(h_3-h_2)$
ORCC2	3—>4	t_3	t_4	$m(h_4-h_3)$
ORCC3	4—>5	t_4	t_5	$m(h_5-h_4)$
ORCH1	6—>7	t_6	t_7	$m(h_7-h_6)$
ORCH2	7—>1	t_7	t_1	$m(h_1-h_7)$

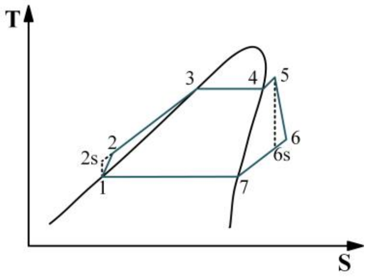

Figure 3: T-S diagram of the ORC in this model

$$forc_s = m\Delta h/\Delta t \tag{1}$$

The turbine work and pump power consumption calculation are given by Eqs.(2-3), which can be calculated from the changes in thermodynamic properties of the working fluid. η_{tur} and η_{pump} a-re isentropic efficiency of the two processes.

$$W_{tur} = m\left(H_5 - H_6\right) = \eta_{tur} m\left(H_5 - H_{6s}\right) \tag{2}$$

$$W_{pump} = m\left(H_2 - H_1\right) = m\left(H_{2s} - H_1\right)/\eta_{pump} \tag{3}$$

3.1.2 Model for pressure-change streams

Constraints of the pressure-change streams are displayed in this part, including temperature changes after pressure operation, mass balance constraints, and calculations for work production of high-pressure streams and work consumption of low-pressure streams. In Eq.(4), $T_{hp,k}^{out}$ and $T_{hp,k}^{in}$ represent outlet and inlet temperatures of the expander for a branch stream *k* of high-pressure stream *hp*.

$$T_{hp,k}^{out} = T_{hp,k}^{in} \left(P_{hp}^{tar} \big/ P_{hp}^{sup} \right)^{(\gamma/\gamma-1)} \tag{4}$$

$$T_{lp,k}^{out} = T_{lp,k}^{in} \left(P_{lp}^{tar} \big/ P_{lp}^{sup} \right)^{(\gamma/\gamma-1)} \tag{5}$$

$$Fhp_{hp} = \sum_{k} Fhps_{hp,k} \tag{6}$$

$$Flp_{lp} = \sum_{k} Flps_{lp,k} \tag{7}$$

$$W_{hp,k} = Fhps_{hp,k} \left(T_{hp,k}^{in} - T_{hp,k}^{out} \right) \tag{8}$$

$$W_{lp,k} = Flps_{hp,k} \left(T_{lp,k}^{out} - T_{lp,k}^{in} \right) \tag{9}$$

3.1.3 Extended Duran-Grossman model

In this section, the purpose is to determine the thermodynamic path of the pressure-change streams. As shown in Figure 2, there are several potential paths for high/low pressure streams to adjust its heat transfer units before and after the pressure operation unit. Duran and Grossmann (1986) proposed a model to deal with the heat integration with variable temperatures or flowrates of the streams and find out minimal utility requirements. To solve the integration problem with changeable cold or hot stream thermal identities, the binary variable y_s is used in that it represents a cold stream when y_s equals to 1. The Duran Grossmann model could be extended to handle a heat integration problem involving streams with changeable thermal identities. As the following equations show, hot and cold utilities can be obtained by calculating the heat deficit $z_H^p(x)$ above the candidate Pinch temperature and the difference in the total heat content between cold streams and hot streams $\Omega(x)$.

$$T_s^p = T_s^{in} + \left(1 - 0.5 \cdot y_s\right) \cdot HRAT \tag{10}$$

$$QSOA(x)^p = \sum_{s \in S} (1 - y_s) FCp_s \left[\max\left\{0, T_s^{in} - T^p + \left(y_s - 0.5\right) \cdot HRAT\right\} - \max\left\{0, T_s^{out} - T^p + \left(y_s - 0.5\right) \cdot HRAT\right\} \right] \tag{11}$$

$$QSIA(x)^p = \sum_{s \in S} y_s \cdot FCp_s \left[\max\left\{0, T_s^{out} - T^p + \left(y_s - 0.5\right) \cdot HRAT)\right\} - \max\left\{0, T_s^{in} - T^p + \left(y_s - 0.5\right) \cdot HRAT)\right\} \right] \tag{12}$$

$$z_H^p(x) = QSIA(x)^p - QSOA(x)^p \tag{13}$$

$$z_H^p(x) \le Q_{hu} \tag{14}$$

$$\Omega(x) = \sum_{s} (1 - y_s) FCp_s (T_s^{in} - T_s^{out}) - \sum_{s} y_s FCp_s (T_s^{out} - T_s^{in}) \tag{15}$$

$$Q_{cu} = \Omega(x) + Q_{hu} \tag{16}$$

3.1.4 Objective function

To better measure the energy efficiency of the system including two forms of energy: heat and work. The objective function of the model is to minimize the Exergy Consumption (EC), which considers the amount of heating and cooling utilities and the work of expanders, compressors, and the Turbine.
The calculation of *EC* is given by:

$$\text{P1: min } EC = Q_{hu}(1 - T_0 / Thu) - Q_{cu}(1 - T_0 / Tcu) - \sum_{lp} \sum_{k} W_{lp,k} + \sum_{hp} \sum_{k} W_{hp,k} - Wnet_{orc} \tag{17}$$

3.2 Model to determine the heat exchanger network structure

Problem P1 can figure out the optimal operating conditions of the ORC and the pressure operation conditions for process streams requiring compression and expansion. There are two main methods for heat exchange network synthesis, Pinch analysis and Mathematical programming, which are widely applied in the chemical industry. To optimize the HEN, this section takes the minimal utility consumption as the goal and designs a heat exchange network by pinch technology, where feasibility rules for matching heat exchange will be used.

4. Case study

In this section, an example is performed to illustrate the application of the proposed method. An ORC using R245fa and R227ea as the working fluid is to be integrated with the process. Two pure organic working fluids and a binary mixture of these two working fluids were integrated with the process and optimized, set superheat to 10 K and mass flow to 5 kg/s. The process stream data is given in Table 2. The temperature for cold utility and hot utility is 288 K (water) and 573 K. Assuming the minimum heat transfer temperature difference is 20 K.

The GA-based optimization process is implemented in MATLAB with appropriate numbers of generations and populations.

Table 2: Data of process streams for the Example

Stream	TIN (K)	TOUT (K)	PIN (MPa)	POUT (MPa)	mCp (kW·K^{-1})
H1	533	450	---	---	5
H2	493	353	---	---	6
HP	424	381	0.3	0.1	3
C1	383	465	---	---	3
C2	303	413	---	---	2
LP	402	466	0.12	0.36	3

The optimization result for three organic working fluids integrated with process streams by the objective of minimum EC is given by Table 3. The minimum exergy consumption is the case using R227ea as organic working fluid and the composite curves is given by Figure 5, from which we can obtain that the minimal consumption of hot and cold utilities are 0 kW and 713.7 kW. A heat exchange network is designed based on above results and 20 K minimum temperature difference. As Figure 4 shows, there is no heating utility used and both high-pressure and low-pressure streams have no split stream, and the type of heat exchanger before pressure operation is different. To reduce overall consumption, a cooling operation is carried out before compression and heating the stream before expansion. There are twelve heat exchangers and two condensers used. Since the interaction of work and heat, there is a competition between ORC and pressure-change streams on work production, both of which can improve heat integration with the process. In this example, the minimal exergy consumption is 70.79 kW without using ORC, which is about 39 kW more than the case using R227ea as working fluids.

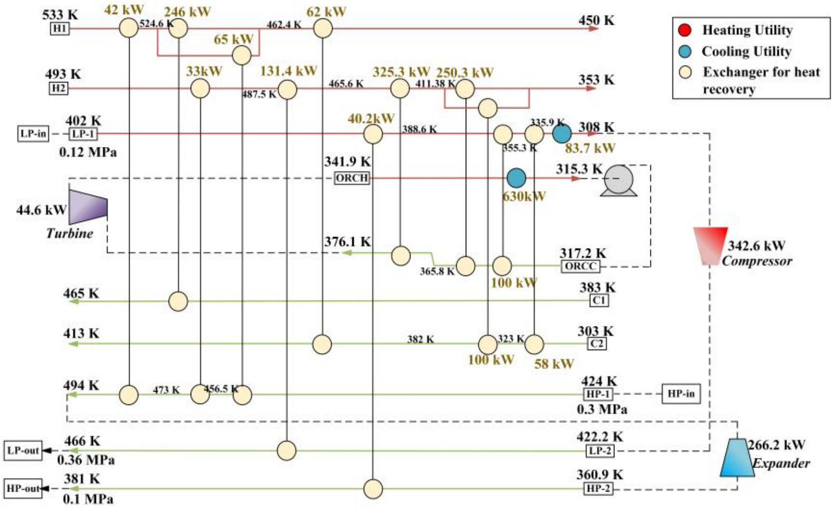

Figure 4: The network configuration of work-integrated HEN coupled with ORC using R227ea with minimal exergy consumption

Table 3: Results for integration of ORC and process using different working fluids

Working fluid	Mass fraction	Evaporation temperature (K)	Condensation temperature (K)	ORC net power output (kW)	Minimal Exergy consumption (kW)	Standard Deviation of the last generation
Non-ORC	---	---	---	---	70.79	--
R245fa	---	417.3	333.2	111.2	93.1	20.48
R227ea	---	365.8	315.8	44.6	31.8	32.97
R245fa: R227ea	0.504	391.2	334.6	66.9	54.62	30.17

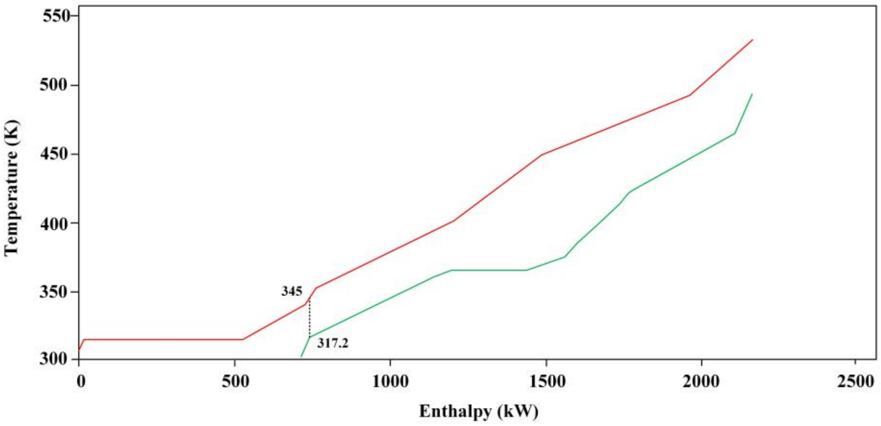

Figure 5: The composite curves for ORC-integrated HEN using R227ea as ORC working fluid

5. Conclusion

A model is proposed to realize the integration of ORC and processes containing variable pressure streams, where heuristic algorithm is applied to get the optimal solution. The objective of the model is minimizing the total exergy consumption of the system and recover the waste heat. A numerical example is conducted to validate the method, comparison of different cases has been made. Dividing exergy consumption by total heat content of the streams, the case that Work-Heat integration with ORC using ‘R227ea’ has the value 1.91 % lower than the case without ORC, which indicates that the integrated ORC system indeed increases the potential energy utilization of the process and can further recover waste heat. In addition, this model pursues the reduction of energy consumption and doesn’t consider the economy of the system, which would lead to an uneconomical configuration with equipment costs. Further work will consider the economic performance of the system and optimize the network configuration based on a balance of energy consumption and economy.

References

Chen C.L., Chang F.Y., Chao T.H., Chen H.C., Lee J.Y., 2014, Heat-Exchanger Network Synthesis Involving Organic Rankine Cycle for Waste Heat Recovery. Industrial & Engineering Chemistry Research, 53, 16924-16936.

Chen Y.T., Wang L., Ye S., Xu Y.Y., Huang W.G., 2020, Simultaneous Optimization Method for Directly Integrating ORC with HEN to Achieve Exergy-Economy Multiobjective. Industrial & Engineering Chemistry Research 59, 21488-21501.

Desai N.B., Bandyopadhyay S., 2009, Process integration of organic Rankine cycle. Energy, 34, 1674-1686.

Dong X., Liao Z.W., Sun J.Y., Jiang B., Wang J.D., Yang Y.R., 2020, Optimization of Organic Rankine Cycle Involving Operating Conditions and Work Fluids and Heat Integration. Chemical Engineering Transactions, 81, 799-804.

Duran M., Grossmann I., 1986, Simultaneous optimization and heat integration of chemical processes. AIChE Journal, 32(1), 123-138.

Linnhoff B., Hindmarsh E., 1983, The pinch design method for heat exchanger networks. Chemical Engineering Science, 38, 745−763.

Lautaro B., Patricio L., Alexis J.V., Zumoffen D., 2022, Generalized simultaneous optimization model for synthesis of heat and work exchange network. Computers and Chemical Engineering, 168, 108036.

Supaluck W., Li S.T., Lee J.Y., 2022, Optimal integration of organic Rankine cycles into process heat exchanger networks: A simultaneous approach. Energy Conversion and Management, 260, 115604.

Wechsung A., Aspelund A., Gundersen T., Barton P.I., 2011, Synthesis of Heat Exchanger Networks at Subambient Conditions with Compression and Expansion of Process Streams. AIChE Journal, 57(8), 2090-2108.

Yee T.F., Grossmann I.E., Kravanja Z., 1990, Simultaneous optimization models for heat integration-I. Area and energy targeting and modeling of multi-stream exchangers. Computers & Chemical Engineering, 14, 1151-1164.

Yu H.S., Fu C., Gundersen T., Matias V., Chang H., 2018, Identifying optimal thermodynamic paths in work and heat exchange network synthesis. AIChE Journal, 65, 549–561.