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Simultaneous Synthesis of Heat Exchanger Network and Utility System Considering Inter- and Inner-stage Heaters

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Heat exchanger network (HEN) and utility system are both important compositions in chemical industry. Heat exchanger network contributes to recover heat from process streams and sometimes consumes external heat resources when heat demand is not satisfied by itself. Rankine cycle-based utility system supplies steams to motivate processes if external heat is needed, meanwhile produces power in turbine. Thus, there is great necessity to synthesize HEN and utility system simultaneously. In this work, a stage-wise HEN superstructure model considering the optimal placement of heaters and matches of streams is presented to integrate with utility system, wherein heaters that consume utility steams are allowed to be placed inside each stage and also between adjacent stages. The selection and allocation of the steams in different pressure levels are optimized considering both power generation in utility system and heat recovery in HEN. A mixed-integer nonlinear programming (MINLP) formulation is formulated for the optimal design of HEN-utility system with minimum total annualized cost (TAC), aiming at trade-off amongst capital cost, fuel cost and income of selling power. At last, a case is studied to demonstrate the application of the proposed method, obtaining a desired HEN configuration with meaningful economic benefits.

1. Introduction

Due to the enormous depletion of energy in industrial chemical processes, notable efforts have been worked on the synthesis of heat exchanger network (HEN), looking forward to promoting the progress of energy conservation and emission reduction tasks. Utility system that supplies thermal and mechanical energies is an essential part of energy management system. HEN interacts with utility system through steams in multiple pressure levels, thus an extended optimization can be exploited if the two systems are considered as a whole. Researches have been performed on the simultaneous synthesis of HEN and utility system, yet traditional HEN superstructure offers limited selections for the arrangement of multi-level steams, restricting the optimization space of the two interacted systems. Therefore, launching a comprehensive study for the integrated HEN and utility system is of great necessity from perspective of overall benefit.

HEN synthesis has been widely studied in view of its important role in energy management system. According to research in recent years, heat recovery efficiency has been further enhanced by retrofitting superstructure of HEN and exploring more potential possibilities of utility utilisation. Ponce-Ortega et al. (2010) developed superstructure allowing the using of utilities in stage, and a disjunctive programming formulation was established to implement the optimization. Na et al. (2015) proposed a modified superstructure with utility sub-stage to improve solving efficiency and considered multiple utilities at the same time. Zhang et al. (2017) presented a stage-wise chessboard model to reduce search region and lower calculation load by using random walking algorithm. Pavão et al. (2018) investigated the location of utilities in any possible stream branch within stage, and an improved hybrid meta-heuristic solution method was presented to handle the resultant complex mathematical model. Above mentioned studies mainly focus on the improvement of structure considering multiple utility allocation. However, there is still additional choice like inter-stage heaters can be added to achieve more rational configuration.

Based on studies of HEN, the simultaneous synthesis of HEN and utility system has also received increasing attention due to their close interactions. Hipolito-Valencia et al. (2013) addressed integration of organic Rankine

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cycles with background processes, aiming at recovering excess heat of low-temperature from process streams in form of mechanical energy. Goh et al. (2016) presented an automated targeting model for the synthesis of HEN with utility system. Optimal allocation of utilities as well as power generation were identified before detailed structure design. In addition to latent heat, the sensible heat utilisation of condensate was also considered by Luo et al. (2016). Luo et al. (2018) launched a multi-objective optimization of water-energy system for the trade-off between water and fuel consumption.

Based on the above analysis, it can be concluded that, current studies of combined HEN and utility system synthesis are still subjected to the traditional presentation of HEN superstructure, and the interactions (generation and utilisation of steams) are not well investigated because the detailed design of utility system is commonly ignored. Thus to solve these problems in this study, utility system is designed considering steam generation in cascade, and the superstructure of HEN is enhanced by introducing new feature for matching arrangement, where heaters can be placed in both inner- and inter-stage locations for heating purpose. This proposed superstructure is presented into a modified MINLP mathematical model. Interconnection constraints are applied to distinguish inner- and inter-stage temperature intervals. Identification constraints are also raised to recognize level of steam used in corresponding heater, which is different from disjunctive programming formulation, because steam in any level can be selected as long as the temperature differences allow. A case study is performed to illustrate the superiority.

2. Problem statement

The problem addressed in this paper is stated as follows: In Rankine cycle-based utility system, steams generated through boiler and turbine are specified with respective pressure level and temperature. For heat exchange task, a set of hot and cold process streams are given with heat capacity flowrates, supply and target temperatures, and heat transfer coefficients. All the cost-related parameters are also given. Purpose of this work is to output an optimal network with minimum total annualized cost (TAC). Here, in addition to the expenditures for cold utility consumption, fuel consumption and equipment installation (for heat exchangers, boiler and turbine), the earning of selling power is also integrated into the objective function, expecting to reach the best trade-off between HEN and utility system. Countercurrent heat exchange is stipulated in the study, and for simplification, heat capacity and heat transfer coefficient of each stream are assumed to be constant.

3. Superstructure

This study presented an optimization-based method to handle the simultaneous synthesis of HEN and utility system. The mathematical model is formulated based on the superstructure depicted in Figure1, wherein two hot streams and two cold streams as well as a three-steam-level utility system are used to present the model. In Rankine cycle-based utility system part, superheated steams are generated in boiler and then extracted as high-, middle- and low-pressure superheated steams in steam turbine, with turbine condense steam extracted and condensed at the end. All the superheated steams are desuperheated by water from deaerator, and the resultant saturate high-, middle- and low-pressure (HP, MP, LP) steams are used in HEN. After heating process streams, the steams condense and returns to deaerator at saturate temperature and then evaporates into steam in boiler, completing a cycle. As indicated, steam generation and utilisation link the two parts. In HEN part, the classic stage-wise superstructure is inherited and developed. Besides coolers and heaters locating at end side of streams, inner-stage and inter-stage heaters are also allowed for each cold stream. In the mathematical model, binary variables are used to present the determination of steam utilisation, and non-linear constraints are required to express the non-isothermal mixing of the stream split branches between adjacent stages.

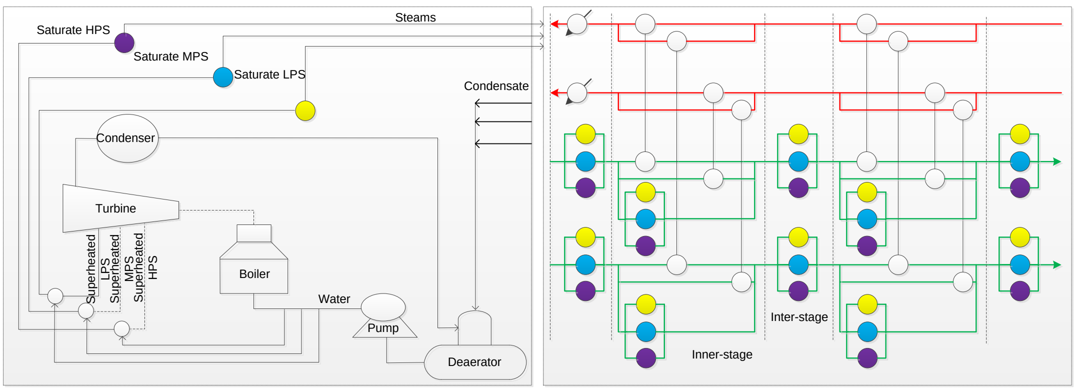


Figure 1: Superstructure for combined HEN and utility system

4. Mathematical model

According to the superstructure proposed above, an MINLP is formulated, which consists of both HEN and utility system, as well as the objective function.

4.1 Model for heat exchanger network synthesis

For HEN synthesis part, the model constraints refer mainly to the total energy balances for each hot and cold process stream, mass and energy balances within each stage, as well as the heat exchange area calculation. The general model for HEN synthesis based on stage-wise superstructure is improved, involving new items to account for the inter- and inner-stage utility heating. For concision, the most important constraints that present the selection of steam level and the calculation of related heat exchange area are given as below.
Heat transfer area $As_{j,k}$ of inner-stage heater is calculated with Eqs(1)-(6).

$$dts1_{j,k,n} = thus_{j,k,n} - tcs_{j,k} + \gamma\left(1 - zhus_{j,k,n}\right) \tag{1}$$

$$dts2_{j,k,n} = thus_{j,k,n} - tj_{j,m} + \gamma\left(1 - zhus_{j,k,n}\right) \qquad m = 2k \tag{2}$$

$$\Delta Ths_{j,k,n} = \left(dts1_{j,k,n} \times dts2_{j,k,n} \times \left(dts1_{j,k,n} + dts2_{j,k,n}\right) \times 0.5\right)^{1/3} \tag{3}$$

$$Asn_{j,k,n} = qhus_{j,k} \times zhus_{j,k,n} \Big/ \left(h \times \Delta Ths_{j,k,n}\right) \tag{4}$$

$$As_{j,k} = \sum_{n} Asn_{j,k,n} \tag{5}$$

$$\sum_{n} zhus_{j,k,n} \leq 1 \tag{6}$$

Heat transfer area $Ahu_{j,k}$ of inter-stage heater is calculated with Eqs(7)-(12).

$$dth1_{j,k,n} = thu_{j,k,n} - tj_{j,m} + \gamma\left(1 - zhu_{j,k,n}\right) \qquad m = 2k \tag{7}$$

$$dth2_{j,k,n} = thu_{j,k,n} - tj_{j,m+1} + \gamma\left(1 - zhu_{j,k,n}\right) \qquad m = 2k \tag{8}$$

$$\Delta Thu_{j,k,n} = \left(dth1_{j,k,n} \times dth2_{j,k,n} \times \left(dth1_{j,k,n} + dth2_{j,k,n}\right) \times 0.5\right)^{1/3} \tag{9}$$

$$Ahun_{j,k,n} = qhu_{j,k} \times zhu_{j,k,n} \Big/ \left(h \times \Delta Thu_{j,k,n}\right) \tag{10}$$

$$Ahu_{j,k} = \sum_{n} Ahun_{j,k,n} \tag{11}$$

$$\sum_{n} zhu_{j,k,n} \leq 1 \tag{12}$$

Wherein subscripts *i, j, k* denote the hot process stream, cold process stream and temperature stage; *m*, *n* denote temperature location and steam level, respectively. $Zhus_{j,k,n}$ and $Zhu_{j,k,n}$ are both binary variables presenting existence of inner- and inter-stage heaters. To avoid the singularity, Eqs(3) and (9) employ the approximation of Chen (1987) to calculate the logarithmic mean temperature difference of heat transfer. Eqs(6) and (12) claim the stipulation that at most one level of steam can be selected for each utility heating.

4.2 Model for utility system design

Heat demand $qsteam_n$ and mass flows $msteam_n$ for saturate steam in level *n* are given by Eqs(13)-(14). Eq(15) denotes power generation of turbine calculated from mass flowrate and enthalpy of superheated steams. Cost of fuel consumption is given in Eq(16) while investment cost of boiler and turbine are given by Eqs(17)-(18) (Chen and Lin, 2012). Energy balance of deaerator as well as energy balance between superheated and saturate steam are given by Eqs(19)-(20). $msteam_{ext,z}$ is mass flowrate of superheated steam extracted from turbine section z. mw_{water} is water flowrate for cooling superheated steam.

$$qsteam_n = \sum_j \left(zhu0_{j,n} \times qh0_j \right) + \sum_j \sum_k \left(zhu_{j,k,n} \times qhu_{j,k} \right) + \sum_j \sum_k \left(zhus_{j,k,n} \times qhus_{j,k} \right) \tag{13}$$

$$msteam_n = qsteam_n \times ahour \times 3600 / lheat_n \tag{14}$$

$$wt^{\text{total}} = msteam_{\text{superheated},z} (enth_{in,z} - enth_{out,z}) \times effturb / 3600 \tag{15}$$

$$C_{\text{fuel}} = \left(lheatin \times \sum_z msteam_{extra,z} \right) \times cfuel \Big/ \left(effboil \times heatcap \right) \tag{16}$$

$$C_{\text{tur}} = 81594 + 18.052 \times wt^{total} / ahour \tag{17}$$

$$C_{boil} = 101840 + \left(3.441 \times \sum_z msteam_{extra,z} \right) \Big/ ahour \tag{18}$$

$$\sum_n \left(msteam_n \times enth_{condensate,n} \right) = \left(\sum_n msteam_n \right) \times enth_{deaerator,out} \tag{19}$$

$$msteam_n \times enth_{sat,n} = mw_{water,z} \times enth_{water} + msteam_{ext,z} \times enth_{ext,z} \tag{20}$$

Wherein wt^{total} denotes the total power generated via turbines. C_{fuel} denotes the cost of fuel consumption, which is related to the mass flowrate of steams and heat content of fuel. C_{boil} and C_{tur} denote the investment costs of boiler and turbine respectively.

4.3 Objective function

Objective of the optimization model is to minimize the TAC, which considers investment cost and profit from power selling. Investment cost is the summation of capital cost (for all heat exchangers, turbine and boiler) and operating cost (for cold utility and fuel). Power selling profit is subtracted in TAC to present its offset to cost.

$$\begin{aligned} \min TAC = & \sum_i CF_{\text{cu},i} \times zcu_i + \sum_i \sum_j \sum_k CF_{i,j,k} \times z_{i,j,k} + \sum_j \sum_n CF_{\text{hu},j} \times zhu0_{j,n} + \sum_j \sum_k \sum_n CF_{\text{hu},j} \times \left(zhus_{j,k,n} + zhu_{j,k,n} \right) \\ & + \sum_i CE_{\text{cu},i} \times \left(Acu_i \right)^\beta + \sum_i \sum_j \sum_k CE_{i,j,k} \left(A_{i,j,k} \right)^\beta \\ & + \sum_j CE_{\text{hu},j} \times \left(A0_j \right)^\beta + \sum_j \sum_k CE_{\text{hu},j} \times \left(Ahu_{j,k} \right)^\beta + \sum_j \sum_k CE_{\text{hu},j} \times \left(As_{j,k} \right)^\beta \\ & + C_{\text{cu}} \times \left(\sum_i qc_i + qc_{condenser} \right) + C_{\text{fuel}} + C_{tur} + C_{\text{boil}} - C_{\text{pow}} \times wt^{\text{total}} \end{aligned} \tag{21}$$

Wherein Acu_j, $A0_j$, $Ahu_{j,k}$, $As_{j,k}$, $A_{i,j,k}$, denote heat transfer areas of coolers, stream-end, inter- and inner-stage heaters, as well as heat exchangers between process streams. zcu_i, $zhu0_{j,n}$, $zhu_{j,k,n}$, $zhus_{j,k,n}$, $z_{i,j,k}$ are binary variables that present the existences of above-mentioned heat exchangers. qc_i is the consumption of cold utilities at stream end side. C_{pow} and C_{cu} are prices of power and cold utility. CE and CF denote the coefficients of area cost and fixed charge respectively, β is the exponent for area cost.

5. Case study

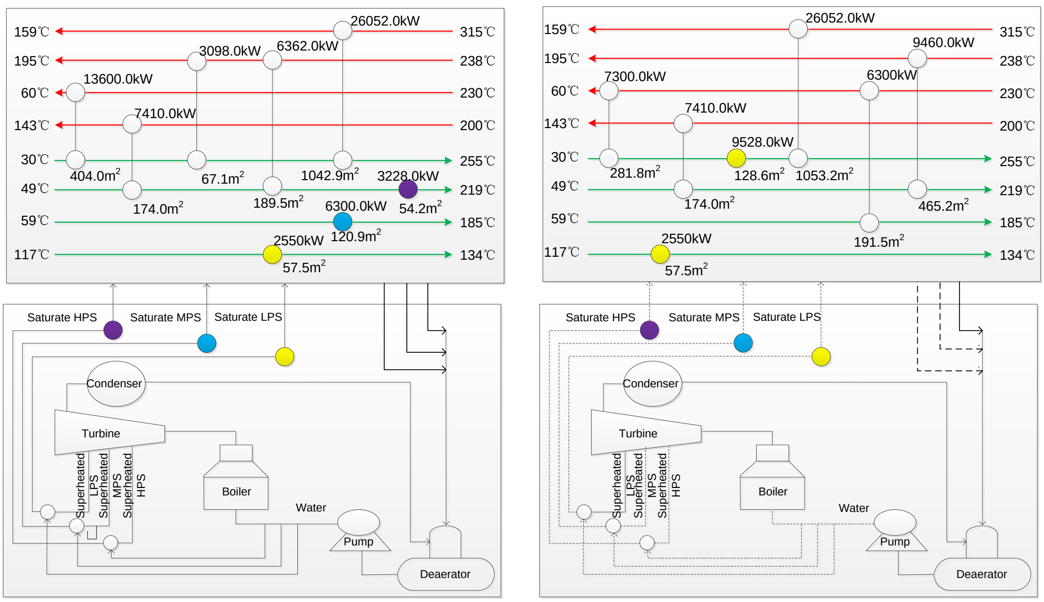
A case study is presented in this section to illustrate the proposed method. Data of hot and cold process streams are given in Table 1. Other parameters used in synthesis include: inlet and outlet temperatures of cold utility are 25 °C and 35 °C; three utility steam options, the low, middle, high pressure levels (LPS, MPS, HPS), are specified with temperatures of 170.4 °C, 198.3 °C and 263.9 °C; Turbine condense water is 45.8 °C. Overall heat transfer coefficient is fixed at 1.0 and 0.5 kW· m^{-2}·°C^{-1} for matches with and without steam, respectively. The price of boiler fuel natural gas and generated power are 0.227 \$·kg^{-1} and 0.076 \$·kWh^{-1} (Luo et al., 2016). Efficiencies of boiler and turbine are set to be 0.9 and 0.7 (Goh et al., 2016).

For comparison, two scenarios are studied by applying different network superstructures: One is the traditional superstructure placing heaters at stream ends only (Scenario 1) and another is the proposed superstructure having inter- and inner-stage heaters included (Scenario 2). In both scenarios, utility system is simultaneously designed with heat exchanger network. As mentioned, three steams options are given for heating purpose, meanwhile the steams in higher level can be saved to cogenerate power before transformed into lower pressure, so the generation and utilisation of steams should be optimized during the design. Both scenarios are presented into MINLP models and solved using BARON (Rosenthal, 2012) in GAMS with near-optimal solutions obtained.

Table 1: Process data for case study

Hot stream	Tin(°C)	Tout(°C)	FC(kW/°C)	Cold stream	Tin(°C)	Tout(°C)	FC(kW/°C)
1	315	159	167	1	30	255	190
2	238	195	220	2	49	219	100
3	230	60	80	3	59	185	50
4	200	143	130	4	117	134	150

The economically optimal network of Scenario 1 is achieved at TAC of 3,599,059 $\$\cdot y^{-1}$, with the network structure given in Figure 2(a). As indicated, HP, MP and LP steams are produced in utility system and then consumed at terminals of cold process streams. Figure 2(b) is the obtained network solution for Scenario 2, in which only LPS is used for heating purpose, not limited at terminal location. This network deployment leads to a 20.35% cost-saving than Scenario 1, as TAC is 2,866,637 $\$\cdot y^{-1}$.



(a) (b)

Figure 2: (a) Structure of Scenario 1. (b) Structure of Scenario 2.

Cost compositions of the two scenarios are listed in Table 2. It can be found that the fuel cost of Scenario 2 (3,240,094 $\$\cdot y^{-1}$) decreases obviously compared with Scenario 1 (4,782,431 $\$\cdot y^{-1}$), and net cost of Scenario 2 is also lower than that of Scenario 1 after subtracting profit of selling power. This is because the superstructure of Scenario 2 contains more possibilities for steam utilisation and LP steam has better economic advantages when supplies energy in view of its additional power generation. Capital costs for equipment are also given in the Table 2. As shown, heat exchangers investment of Scenario 2 (748,222 $\$\cdot y^{-1}$) is much higher than that of Scenario 1 (699,045 $\$\cdot y^{-1}$). This is because the utilisation of steam in low temperature decreases the heat transfer temperature difference between hot utility and cold process streams, thus the required heat transfer area and corresponding capital investment in Scenario 2 are higher than Scenario 1. While due to the reduction of fuel consumption, turbine and boiler investment of Scenario 2 (301,769 $\$\cdot y^{-1}$) is lower than Scenario 1 (364,921 $\$\cdot y^{-1}$). Thus, equipment investment of the two scenarios makes nearly no difference. In total, using the improved superstructure, significantly lower fuel consumption can result in better overall performance.

Table 2: Results of case study

	Scenario 1	Scenario 2		Scenario 1	Scenario 2
Cost of fuel($·y-1)	4,782,431	3,240,094	Heat exchangers investment($·y-1)	699,045	748,222
Boiler investment($·y-1)	212,203	176,611	Profit of selling power($·y-1)	2,395,504	1,467,250
Turbine investment($·y-1)	152,718	125,158	TAC($·y-1)	3,599,059	2,866,637

From the case study, it is concluded that utility system should be incorporated with HEN in detailed design, which can realize the trade-off amongst fuel cost, equipment investment and power selling profit of the entire system through the reasonable generation and distribution of steams. What's more, the placement of inner- and inter-stage heaters would produce extra benefit in terms of the gradient using of multi-level steams.

6. Conclusions

This paper has proposed an optimization-based approach for the simultaneous synthesis of HEN and a Rankine cycle-based utility system. In the improved superstructure of HEN, both inner- and inter-stage heaters are considered to include more distribution possibilities of steam utilities. The generation and distribution of steams in different pressure levels are optimized to couple the two systems, and the operating conditions are set as variables to minimize the TAC of the entire system. In case study, meaningful economic benefit is achieved with 20.35% cost saving than that of original stage-wise superstructure, demonstrating that the proposed method is able to offer more reasonable utilisation of steams by considering more structural options of matches between cold streams and hot utilities. In the future, works will be aimed at the solution strategy for larger scale integration, such as the heat integration problem for industrial park.

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