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An Efficient Sequential Approach for Work-Heat Exchange Networks Synthesis Combined with Meta-Heuristic Strategies

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The optimal integration of work and heat has attracted increasing attention due to its paramount significance in achieving considerable energy and cost savings. However, the strong interactions between temperature, pressure, heat and work, in addition to unclassified stream identities, represent great challenges for optimization of work-heat exchange networks (WHEN). Quantities of binary variables and non-convexities to cope with highly nonlinear relations and identification of stream identities lead to a complex mathematical model which cannot ensure the global optimal solution and even be unable to obtain feasible solutions. To surpass these difficulties, this paper proposes a sequential approach for WHEN synthesis based on a superstructure-based model combined with meta-heuristic strategies. The work exchange networks (WEN) configuration is firstly derived by solving a MINLP model based on the superstructure method. Afterwards, several meta-heuristic strategies in terms of thermodynamic analysis are proposed for the identification of streams identities (cold or hot), thus facilitating the subsequent heat integration through heat exchange networks (HEN) synthesis between the determined cold and hot streams. A case study is conducted to access the efficacy of our proposed method, where the results show that the sequential approach is highly efficient for WHEN synthesis with more mechanical and thermal energy recovery as well as considerable savings in total annual cost.

1. Introduction

Nowadays, pressure manipulation has become a significant part of energy-intensive processes, particularly for ammonia and synthetic methanol synthesis, oil refineries as well as cryogenic production of liquefied natural gas (LNG) (Onishi et al., 2015). In such processes, the integration of work, as another equally important energy transfer form analogous to heat, is critical for attaining significant savings in energy consumption. In contrast to conventional heat exchange networks (HEN), the work exchange networks (WEN) which focus on the feasible matches of expanders and compressors, take the dominating responsibility for the energy integration due to their decisive acts on the increment of energy efficiency. As important contributions to mechanical energy recovery through direct work exchangers, some approaches for synthesizing WEN were investigated, including graphical integration approaches (Zhuang et al., 2017a), a thermodynamic modelling and analysis approach (Rankouhi and Huang, 2017), improved transshipment model (Zhuang et al., 2017b), and extended superstructure model (Zhuang et al., 2017c).

Due to the strongly interactive relationship between work and heat, there is a growing body of literature that recognizes the importance of simultaneous synthesis of work and heat exchange networks (WHEN). Huang and Karimi (2016) presented a superstructure-based mixed-integer nonlinear programming (MINLP) optimization model for simultaneous synthesis of WHEN at the lowest total annual cost (TAC). Onishi et al. (2017) developed a multi-objective optimization model for WHEN synthesis, in which their results heightened the significance for the appropriate heat integration between pressure adjustment stages in order to achieve the optimal balance between economic and environmental performances. Recently, Onishi et al. (2018) introduced a Mathematical Programming model combined with Pinch Location Method for work and heat integration without classified process streams. Nair et al. (2018) proposed a generalized framework for integrating heat and work

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simultaneously based on the strategies that do not pre-classify stream identities and allow phase changes and pressure changes for streams with no net pressure change. Overall, the above-mentioned studies are limited to computationally challenging problems with highly non-convex issues. To overcome this deficiency, based on the thermodynamically heuristic rules proposed by Fu and Gundersen (2017), Yu et al. (2019) developed an extended Duran-Grossmann model for synthesizing WHEN with identification of optimal thermodynamic paths of pressure changes. Inspired by their work, a sequential approach for direct work and heat exchange network synthesis is proposed in this article.

This paper proposes a step-wise model for work and heat exchange network synthesis based on an extended WEN-HEN superstructure combined with meta-heuristic strategies. The work exchange networks configuration is firstly derived by solving a MINLP model with the objective of maximum mechanical energy recovery. Subsequently, several meta-heuristic strategies are proposed for the identification of streams identities (cold or hot), thus facilitating the heat integration through heat exchange networks between the determined cold and hot streams. To verify the methodological effectiveness, a case study supplied from the literature is investigated.

2. Problem statement

Given a set of high-pressure and low-pressure streams with known inlet and outlet states (temperature, pressure, flowrates, heat capacities and heat transfer coefficients etc), an optimal work and heat exchange networks configuration is designed in a sequential way, by achieving the maximum mechanical energy recovery firstly and then minimizing the total annual cost, which considers the contributions of operational expenditure for utilities and capital expenditure for units.

It should be emphasized that the direct work and heat exchange networks synthesis is a complex task, in spite of adopting a sequential WEN-HEN model. Therefore, the focus of this article is to seek for an optimal WHEN configuration with enhanced energy integration. In order to simplify the synthesis procedure, the assumptions that have been commonly used in the previous work (Zhuang et al., 2019) are used, as the rigorous operational mode of individual device is beyond the scope of this article.

3. Mathematical programming model for WHEN synthesis

3.1 WEN-HEN coupled superstructure

Note that when the mechanical energy is recovered through direct work exchangers operated under adiabatic condition, the temperature will be changed within the system. Under such circumstances, the HEN synthesis should be performed within the WEN design to promote heat integration, thus improving the energy efficiency of the whole WHEN. In this article, the formulations for direct WHEN synthesis are on the basis of the WEN-HEN coupled superstructure, as shown in Figure 1, which is an extension of the work by Zhuang et al. (2019).

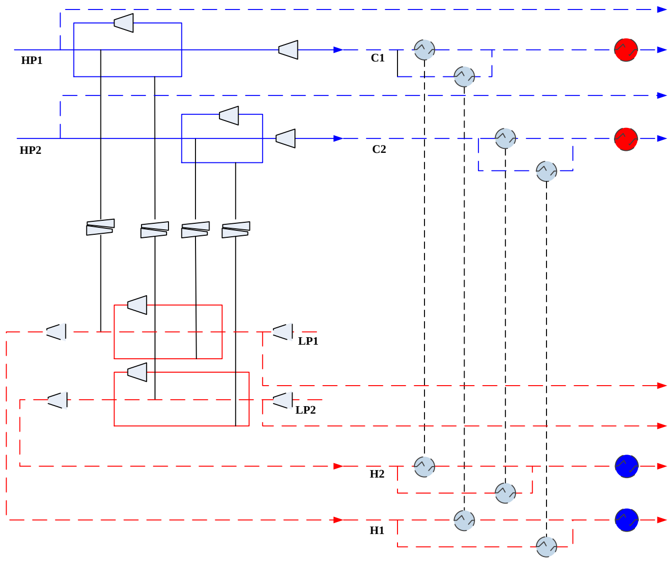

Figure 1: The WEN superstructure coupled with the HEN superstructure

The generation of the WEN superstructure coupled with HEN superstructure introduced in this work is centred the main ideas as follows:

(1) As presented by Zhuang et al. (2019), the direct WEN-HEN superstructure consists of K stages, where K is equal to the larger number among the number of high-/low- pressure streams. At each stage of the WEN superstructure, the utility expanders and compressors in parallel should be considered, and it is also essential to allow for the optimization of utility compressors in series for low-pressure streams. The improvement in this work is that the inlet temperature of each stage is regarded as decision variable.

(2) The key strategy is to determine the cold and hot identity of process streams. Different from the fact that binary variables are used for identification of stream identity in Nair et al. (2018), the cold and hot identities of process streams between the stages of WEN and exiting the WEN are determined separately. Under the former, the stream identity is determined by the utility compressors/expanders based on our previous work, in which five meta-heuristic rules and three strategies have been proposed for introduction of heat-exchange equipment into the WEN (Zhuang et al., 2017d). In addition to the latter, it is recognized by the comparison between the outlet temperature of streams and the exit temperature when they pass through the direct WEN, as derived by Eq(1) - Eq(2). If the outlet temperature of streams is higher than the exit temperature from WEN, the streams are regarded as cold streams; otherwise, the streams are considered to be hot streams.

$$T_{HPi,WEN}^{out} = \left(\frac{P_{HPi}^{out}}{P_{HPi}^{in}} \right)^{\frac{\gamma - 1}{\gamma}} \cdot T_{HPi}^{in} \tag{1}$$

$$T_{LPj,WEN}^{out} = \left(\frac{P_{LPj}^{out}}{P_{LPj}^{in}} \right)^{\frac{\gamma - 1}{\gamma}} \cdot T_{LPj}^{in} \tag{2}$$

(3) From Figure 1, it can be seen that the inlet temperature of streams in HEN corresponds to the exit temperature of streams through WEN or the intermediate temperature of streams between the stages of WEN, and the heaters and coolers are respectively allocated at the end of cold and hot streams to attain their respective target temperatures.

3.2 Model formulations for sequential synthesis of WHEN

In this context, the proposed mathematical model for direct WHEN synthesis is formulated as a MINLP model, where the objective function and corresponding constraints are generated on the basis of the aforementioned superstructure. Since a sequential approach is presented hereby, thus the optimal configuration is derived in accordance with the maximum mechanical recovery first for WEN synthesis and then the minimum total annual cost (TAC) for WHEN synthesis, as expressed by Eq(3) - Eq(4).

$$\max \quad W_{Recovery} = \sum_{k} \sum_{HPi} \sum_{LPj} W_{HPi,LPj,k} \tag{3}$$

$$\min \quad TAC_{WHEN} = CAPEX_{WHEN} + OPEX_{WHEN} \tag{4}$$

Wherein, the total annual cost is composed of capital investment (CAPEX) and operational expenditure (OPEX). Due to the limit of the six-page manuscript, the detailed formulation for each constraint cannot be shown in this paper. However, how to synthesize the WEN and HEN in a step-wise way is based on the previous work proposed by Zhuang et al. (2019) and the well-known superstructure-based model presented by Yee and Grossmann (1990).

In spite of lacking the model description in detail, this article still provides an efficiently sequential approach for synthesis of WHEN to sharply reduce the thermal and mechanical energy consumption. On the basis of the two coupled superstructure-based models for synthesis of direct WEN and HEN described above, a design flowchart is developed to obtain the WHEN configuration with the goal of maximizing mechanical energy recovery and minimizing TAC respectively, as illustrated in Figure 2. This flowchart shows that the first step is to derive the optimal direct WEN configuration according to the proposed superstructure-based MINLP model. Subsequently, to obtain the final WHEN configuration, the stream-split superstructure for HEN is coupled with that for the direct WEN, which is joined together by determination of the cold or hot identity of streams. Furthermore, the developed method is general for synthesizing direct WEN of any size coupled with heat integration, which can be coded as a computational program using GAMS 24.1 with BARON as the MINLP solver on a computing platform with 3.6 GHz Intel Core i7-4790 CPU and 4 GB of RAM.

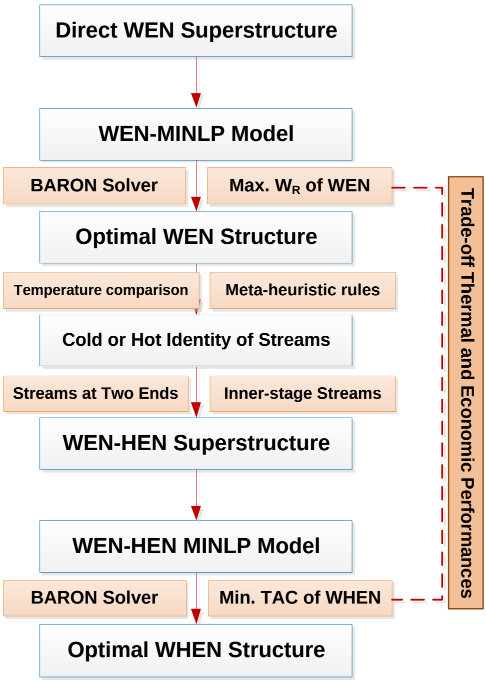

Figure 2: Flow chart of the presented method

4. Case study one

In this section, a case study selected from Zhuang et al. (2017a) is conducted, also performed by Rankouhi and Huang (2017), to illustrate the feasibility and efficacy of the proposed method. This case involves three high-pressure and two low-pressure streams. Table 1 lists the detailed stream data. Likewise, the minimum pressure difference is taken as 70 kPa. In addition, the individual coefficients of heat transfer for process streams and utilities are equal to 0.1 and 1.0 kW/(m^2·K). To model the pressure manipulation units, it is assumed to be an isentropic efficiency of 1.0 and 0.75 for direct work exchangers and stand-alone compressors or expanders respectively, as well as a Joule-Thomson coefficient of 1.961 K·MPa^{-1}.

Table 1: Stream data for Case study one

Streams	P_{in} [kPa]	P_{out} [kPa]	F [kg·s^{-1}[	T_{in} [K]	T_{out} [K]	CP [kJ·kg^{-1}·K^{-1}]
HP1	850	100	3	600	430	1.432
HP2	960	160	5	580	300	0.982
HP3	800	300	2	690	300	1.046
LP1	100	510	3	300	700	1.432
LP2	100	850	3	300	600	1.432

Due to the purpose for sequentially synthesizing the direct WEN coupled with HEN in this example, thus the work-transfer devices operated under adiabatic condition are considered. In the first step, to facilitate the direct WEN synthesis, a three-stage superstructure with stream splits for optimal direct WEN configuration is proposed and a MINLP model is described to identify the optimal solution in term of maximizing the mechanical energy recovery. Afterwards, the WEN can be coupled with heat integration through HEN synthesis to derive the optimal WHEN configuration. Following the procedure in Figure 2, the final WHEN configuration is obtained using a sequential approach. As a consequence, the corresponding comparison with solutions obtained by other authors is listed as follows in detail.

From Figure 2 and Table 2, it can be seen that the optimal WEN configuration is designed with four direct work exchangers to recover 2,634 kW of mechanical energy, two utility compressors and only one utility expander, where nearly 95.1% of mechanical energy is recovered. Compared with the solutions obtained by the literature, a 48.1% and 31.9 % increase in mechanical energy recovery is achieved. In addition, the derived optimal configuration only involves seven units, also less than the number of units in the corresponding literature.

Table 2: Comparison of energy recovery and utility consumption in the WEN for Case study one

Method	W_R [kW]	W_{Com} [kW]	W_{Exp} [kW]
Rankouhi and Huang (2017)	1,778	1,628	993
Zhuang et al. (2017a)	1,997	1,409	774
This work	2,634	772	137

In the succeeding step, the cold and hot identity of streams should be determined by Eq(1) and Eq(2) and the strategies in the previous work prior to HEN design. The outlet temperatures of the high-pressure and low-pressure streams leaving the direct WEN configuration are calculated using Eq(1) and Eq(2), which reaches a conclusion that HP1, LP1 and LP2 are regarded as cold streams while HP2 and HP3 are hot streams. Interestingly, it can be found that HP3 generates two hot streams between stages of WEN and exiting WEN.

Afterwards, the traditional stage-wise superstructure with stream splits for Heat Integration is adopted to design the optimal HEN configuration. An interesting conclusion can be drawn that five exchangers with 511.3 kW of thermal energy recovery are needed in the optimal HEN. In addition, there exist two coolers (60.7 kW and 216.1 kW) allocated on H2 and H3 and two heaters (889.3 kW and 176.1 kW) allocated on C2 and C3 to meet the requirement of target temperatures. Based on the coupling of the WEN and HEN, the final WHEN configuration can be derived, as illustrated in Figure 3. Moreover, the benefit of savings in TAC of the WHEN configuration derived by our proposed method is summarized in Table 3, where the TAC of the WHEN is 1,975,427 $\$\cdot y^{-1}$, a 19.9 % decrease over that without integration.

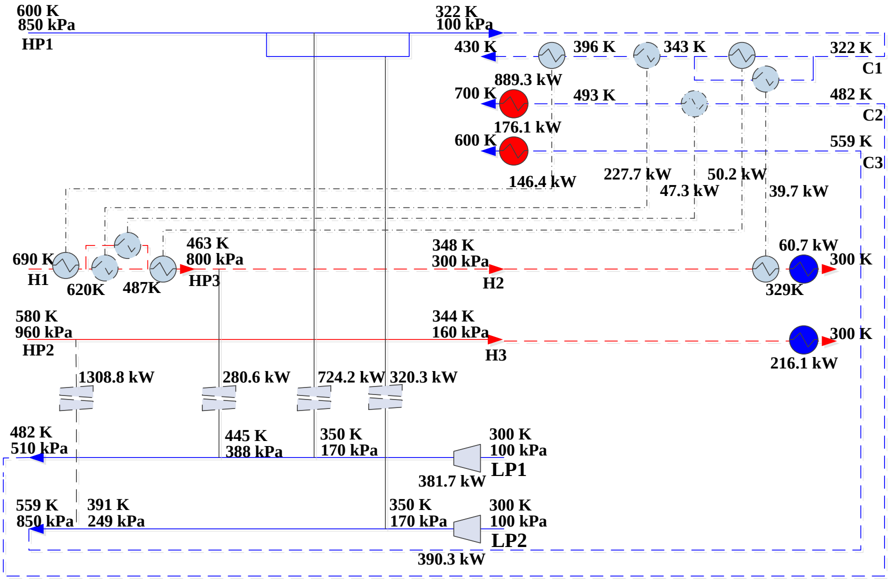

Figure 3: The optimal work and heat exchange networks configuration obtained for the case

Table 3: Cost comparison of WHEN obtained by the proposed model with no integration

Method	CAPEX [$·y-1]	OPEX [$\$\cdot y^{-1}$]	TAC [$\$\cdot y^{-1}$]
No integration	1,115,044	1,351,526	2,466,570
This work	935,135	1,040,292	1,975,427

5. Conclusions

Thermal and mechanical energy recovery is a significantly prospective issue in energy efficiency improvement. Despite the growing approaches for work integration, few superstructure-based methods are presented to achieve the synthesis of direct WEN coupled with HEN synthesis. To surpass this limitation, an efficient sequential method for synthesizing direct WEN coupled with heat integration is developed in this article. First, an efficiently extended WEN stream-split superstructure coupled with the traditional HEN superstructure is presented, considering the Heat Integration both between stages of WEN and exiting the WEN. Subsequently, a MINLP model with the goal of maximizing mechanical energy recovery and minimizing TAC is formulated for the optimal trade-off between thermodynamic and economic performances. The proposed model attains the better mechanical energy goal that indicates more mechanical energy is recovered by fewer work-transfer devices than the methods in literatures. In the case study, it gives a WHEN configuration with 19.9 % lower TAC than a base configuration without integration.

Note that the temperature variation of streams through work-transfer devices will promote Heat Integration while HEN synthesis will also change the stream temperatures prior to WEN so as to facilitate the work integration. To this end, this article presents an essentially sequential approach to synthesize direct WEN coupled with heat integration. It is conceivable that the heat integration between stages in the direct WEN superstructure should be further optimized by concentrating on the cold or hot identity of streams as decision variables, in order to enhance the compression and expansion process, which truly fulfils the simultaneous synthesis of direct work and heat exchange networks in the near future research.

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