



Process Systems Engineering and Process Safety

Integration of energy recovery network including recycling residual pressure energy with pinch technology

Jianqiang Deng^{1,*}, Zheng Cao¹, Dongbo Zhang², Xiao Feng¹¹ School of Chemical Engineering and Technology, Xi'an Jiaotong University, Xi'an 710049, China² Shaanxi Coal and Chemical Technology Institute Co., Ltd, Xi'an 710070, China

ARTICLE INFO

Article history:

Received 12 January 2016

Received in revised form 22 July 2016

Accepted 23 July 2016

Available online 1 September 2016

Keywords:

Integration

Process systems

Heat exchanger network

Work exchange network

Pinch technology

Optimization

ABSTRACT

Work exchange is a promising innovative technology in recovering residual pressure energy. However, at the systematic level, the comprehensive utilization of different energy resources in an energy system has become an issue of concern. In this work, a systematic approach is proposed, one that successively integrates heat, work and adjusts operation parameters. A detailed procedure for building a heat-work coupling transfer network is provided. The synthesis mainly consists of constructing a work exchange sub-network with pinch analysis based on positive displacement type work exchangers. Simultaneously, another kind of sub-network based on turbine-type work exchangers is built as a schematic comparison. The influence of applying a positive displacement work exchanger on the system is investigated. Finally, as a case study, a renovation design of a typical rectisol process in the coal-water slurry gasification section of an ammonia plant is presented. The results show that the added work exchanger has little impact on the existing heat exchange sub-network. Moreover, extra pressure energy is recovered by coupling the transfer network. It is concluded that the heat-work systematic design is a promising and powerful method to use energy more efficiently.

© 2016 The Chemical Industry and Engineering Society of China, and Chemical Industry Press. All rights reserved.

1. Introduction

In recent years, energy-saving in the energy and chemical industry has gone through a stage of process integration, i.e., the entire system is deemed as an organic whole and the work focus is the global optimum design. The two most common forms of energy are heat and pressure. At the beginning of integration technology development, the recovery and integration of heat energy is generally accepted as a key consideration. Many integration technologies, such as mathematical programming technologies and pinch technology, have been proposed for optimizing the heat exchanger network (HEN). In particular, pinch technology is a simple and efficient method for process optimization, and presents a clear overall view of energy consumption efficiency [1]. In recent decades, pinch technology has led to the recovery of large amounts of heat energy through the proper design of HEN, and it has also been applied in hydrogen network and water network optimizations, benefiting the entire process with minimum utility consumptions and cost-savings [2,3].

In addition to thermal power plants, compression or boosting is a major consumer of energy in many chemical plants, including those producing Liquefied Natural Gas (LNG), refineries, air enrichment and ammonia, etc. Some industrial streams need work for compression,

while others can export work through expansion. Traditionally, the work produced or required can be converted into electric energy for further usage or integration. Han *et al.* [4] developed an online optimization system and applied it to the condensing steam turbine network of a chemical plant. An optimization design was formulated by utilizing a developed model to maximize the total electric power recovery from the steam turbine network. Aspelund *et al.* [5] proposed a graphical heuristic methodology based on extending traditional pinch analysis with exergy calculations to minimize energy requirements (total shaft work) in sub-ambient processes. Similarly, Shin *et al.* [6] proposed a Mixed Integer Linear Programming (MILP) formulation for optimizing boil-off gas compressor operations to minimize the total average power consumption in an LNG receiving and re-gasification terminal. El-Halwagi *et al.* [7] introduced a targeting pinch diagram for the integration of heat and power generation process, and the optimal steam flows and process target of cogeneration were rapidly identified. Del Nogal *et al.* [8,9] reported a model able to obtain an optimal power plant system for utility networks. Appropriate gas/steam turbines as drivers were matched with compressor stages by using mathematical programming methods, and the developed methodology was applied to a LNG case study.

In fluid process systems, whenever a high-pressure fluid stream (stream HP) is depressurized, a potential for pressure energy recovery exists. However, pressurizing a low-pressure fluid stream (stream LP) always requires compression work. Optimal integration or matching

* Corresponding author.

E-mail address: dengjq@mail.xjtu.edu.cn (J.Q. Deng).

of the required booster and expansion devices may lead to significant savings in energy. Cheng *et al.* [10] proposed the concept of a work exchanger (WE) in 1960, and described the basic working process of a positive displacement-type work exchanger (PDWE). Based on the working principle, work exchangers can be classified as PDWE or turbine-type (centrifugal type) WE. The PDWE is an isobaric energy recovery device characterized by its working principle. It can be classified as piston type pressure exchanger and rotary pressure exchanger. The former uses a pair of stationary cylinder where pistons reciprocate regularly associated with valve motion. The latter uses a cylindrical rotor with a plurality of open-ended ducts, and the rotor spins between two end covers to realize a continuous pressure exchange process [11]. Because the hydraulic energy is directly transferred between high pressure stream and feed stream, the efficiency of PDWE is higher than that of turbine-type WE [12]. Investigations show that PDWEs have an energy transfer efficiency of 92%–97% [13–15], while turbine-type WEs have an efficiency of 72%–75% [13,16]. Currently, work exchange is successfully applied in worldwide seawater reverse osmosis (SWRO) desalination process, where the PDWE contributes to as much as 60% of energy savings in the RO process [17]. An RO desalination demonstration project operated in Changdao and in Shengsi suggests the PDWE in such plants can decrease the energy consumption to $4.0 \text{ kW} \cdot \text{h} \cdot \text{m}^{-3}$ for freshwater production [18].

Based on the similarity of the heat and mass transfer process, Huang and Fan [19] proposed the work exchange network (WEN) in 1996. By applying the basic principles of energy conservation, necessary and sufficient conditions were derived to identify feasible stream matching in work exchangers. Afterwards, Razib *et al.* [20] modeled the details of compressor and turbine operating curves to identify high-pressure and low-pressure streams that could be matched for work exchange via a turbine-type WE. Considering the characteristics of the PDWE, Liu *et al.* [21] applied a graphical integration method in the stream-matching process. This allowed for the maximum energy recovery and optimal network structure to be simultaneously identified. Pressure energy exists not only in liquid streams but also in gas streams. Deng *et al.* [22] analyzed the performance of gas–gas work exchangers based on the energy conservation law and the real-gas law. It was proposed that a heat-work coupling transfer network could be a more flexible way to recover energy in gas streams. Onishi *et al.* [23] presented a superstructure for HEN synthesis by adjusting pressure levels of process streams to improve heat integration. The mathematical model was developed using generalized disjunctive programming and reformulated in mixed-integer nonlinear programming. It indicated that the integration of heat exchange and pressure manipulation equipment could decrease the total annualized cost.

Energy integration on a large scale is the current trend in technology development. However, as indicated by the above investigations, there are very few studies focused on WENs, and especially on the heat-work coupling transfer network. Currently, pinch technology has been successfully applied in HENs with simple, visualized and flexible characteristics. Therefore, a systematic approach and a detailed scheme including recycling residual pressure energy with pinch technology are proposed to construct a heat-work coupling transfer network. Because of its high energy transfer efficiency, the PDWE has been selected to build a WEN in this work. For comparison, how to build a WEN based on turbine-type WEs is also discussed. Related issues, such as heat transfer in the device, starting mode, *etc.*, are analyzed in a practical work transfer process on a coupling network. Finally, as a case study, a typical rectisol process in a coal-water slurry gasification section of synthetic ammonia is chosen to demonstrate the detailed synthesis process.

2. Problem Statement

Original streams are a set of liquid streams with different temperatures and pressures. Since it is possible to transfer both heat and work among these original streams, the optimized matching between each

stream constitutes a complicated heat-work coupling transfer network. To develop a reasonable matching scheme based on efficient and logical procedures has become the main content of this integration design. The aim of the integration design is to make effective use of heat energy and pressure energy from original streams. As this is an optimization problem, the given parameters of each original stream are fluid properties such as composition, density, viscosity and thermal conductivity, and operation parameters such as the flow rate, pressure and temperature. Besides the required parameters set in the heat exchange process, corresponding parameters in the pressure exchange process have also been previously set. This includes the pressure drop of each work exchanger, the minimum driving pressure differential (ΔP_{dr}), the lowest economical pressure drop (ΔP_{min}) and the minimum economical indicated work. Relevant variables include the flow rate, pressure and temperature of each stream in the new heat-work network. The optimization target is to find the matching scheme with the highest energy recovery rate.

3. Systematic Approach and Procedure

In process design, pinch analysis is applied as an efficient tool to guarantee minimum energy levels in design of HEN. Since work and heat have similar transfer mechanisms and analogous exchange network designs, it is therefore possible to apply pinch technology to the design and optimization of WENs. By analogy with the temperature pinch point in an HEN, the place with the minimum pressure difference in a WEN is defined as the pressure pinch point. Similarly, the pressure pinch point can be obtained from the composite curve of a simple WEN, while the problem table method is more efficient for complex WENs with more streams. Once the pinch pressure is obtained, the matching rules and restrictions involved by pinch position helps to identify the various matching schemes and to select the most appropriate one for integration. The basic systematic approach on a heat-work coupling transfer network can be described as follows: An HEN is constructed first, which commonly determines the main effect of energy recovery. This step can be neglected when reforming an existing exchange network because its HEN is usually already made. It is then necessary to analyze basic data and build a WEN based on pinch technology. Since the WEN always alters the state parameters of the previous HEN to some extent, the final heat-work coupling transfer network can be achieved only by adjusting the operation parameters of the network. What needs to be noted is that there can be different WEN schemes established by using different types of work exchangers. Fig. 1 shows

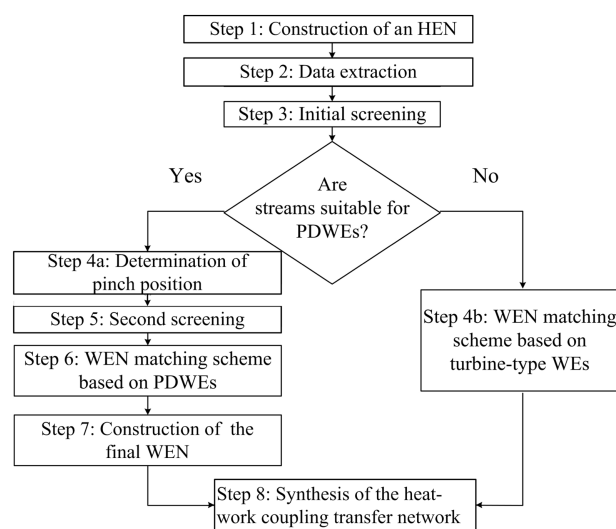


Fig. 1. Scheme and steps to construct a heat-work coupling transfer network.

the systematic approach to building a heat-work coupling transfer network using pinch analysis, with a detailed explanation below.

Step 1: Construction of an HEN

Heat recovery has played a very important role in energy-saving technology. The working procedures of an HEN optimal design are relatively mature. There are several reasons for constructing an HEN in advance:

- (1) Recovered heat is commonly an important part of the total recovered energy in an energy or chemical system. Thus, it is necessary to analyze the heat recovery first and build an HEN in advance.
- (2) Stream pressure shows little change in the heat transfer process. When an HEN has been constructed, the pressure distribution of the system remains relatively stable, and this provides maximal recovery potential of the pressure energy for a WEN.
- (3) After the HEN design process, all system node temperatures can be deemed as known data. A work exchanger can then be located at the lower temperature position of a stream, and material requirements can be reduced accordingly. This also provides a relatively benign operational environment when operating a WEN.
- (4) The temperature variation of a stream flowing through the PDWE is very small. A newly added WEN has a small impact on the previous HEN.
- (5) Because an HEN usually exists in a practical energy or chemical process, the systematic approach used in this study can be directly used in a renovation project.

Step 2: Data extraction

The basic data mainly includes pressure, temperature and flow rate. According to changes in pressure and flow rate during the process, the streams as optimized objects of the WEN are picked out. Among these, the streams providing pressure energy are defined as work sources, while the streams requiring work are defined as work sinks.

Since liquid streams are assumed to be incompressible, the volume change and temperature effect on the work exchange process are neglected. In this case, the amount of indicated work W_{ind} can be calculated based on the pressure difference ΔP between original pressure and target pressure [19],

$$W_{\text{ind}} = V \cdot \Delta P \quad (1)$$

where V is the volumetric flow rate of a stream.

Step 3: Initial screening

In practical applications, there are more restrictions in the work transfer process than that in the heat transfer process:

- (1) The original pressure of the work source ($P_{\text{HP},o}$) must be greater than the target pressure of the work sink ($P_{\text{LP},t}$), and the target pressure of the work source ($P_{\text{HP},t}$) must be less than the original pressure of the work sink ($P_{\text{LP},o}$). This restriction exists mainly in the PDWE, such as for DWEER and PX commercial products. As shown in Fig. 2, the inflow streams in the cylinder can be discharged and the transfer process can be accomplished only when $P_{\text{HP},o}$ is higher than $P_{\text{LP},t}$ and $P_{\text{HP},t}$ is lower than $P_{\text{LP},o}$ in each cycle. In this study, the minimum pressure difference required to push the piston in one piston stroke of PDWE is 0.1 MPa [10,20].

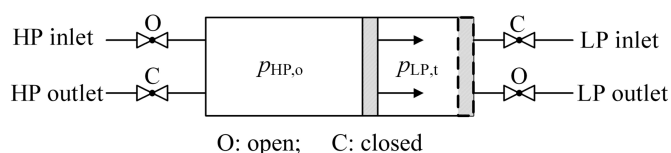


Fig. 2. Pressurization process in a cylinder.

- (2) The work transfer process between two streams must occur in the same transfer device or in two interconnected devices with the same shaft. The distance between the two streams is limited to a certain range. This restriction is particularly important for an actual engineering process.
- (3) According to pinch technology, when the driving force near the pinch is tiny, the increased number of work exchangers will not significantly improve the energy recovery efficiency. Based on this, the lowest economical pressure drop near the pinch point ΔP_{min} is set to 0.2 MPa. In addition, a stream has a certain amount of recoverable pressure energy when its flow rate is large, regardless of the pressure level. A WE is deemed economically feasible to be set when a stream with the indicated work is greater than 5 kW. If a stream has little exchangeable pressure energy, it cannot serve as the exchanging object when considering equipment investment and operational costs.

In view of the above-mentioned restrictions, this work proposes a two-stage screening method for choosing streams. Initial screening is carried out when the pinch point is unknown. According to restriction (3), the streams with small exchangeable pressure energy and the completely unfit pressure ranges should be ruled out, and marked as “N”. A Turbine-type WE can be used in broad work conditions without considering restriction (1). Then streams that only use the turbine-type WE for pressure energy recovery are selected and labeled as “T”. The rest of the streams can be used as work exchange objects for the PDWE, and temporarily marked as “Y”. By singling out the streams that are suitable for the PDWE matching scheme, the matching workload in subsequent steps is decreased.

The values of work exchanger efficiency and pump efficiency are based on those most commonly found in the literature. The efficiency of a centrifugal pump with a large flow rate (flow rate no less than $50 \text{ m}^3 \cdot \text{h}^{-1}$) is 80%, while that of a smaller pump (flow rate less than $50 \text{ m}^3 \cdot \text{h}^{-1}$) is 65% [24,25]. The energy transfer efficiency of a turbine-type WE is 75% [16]. Based on a large number of applications data for SWRO, it is reasonable to set the energy transfer efficiency of a PDWE to 94%. As PDWEs are proposed as preferred equipment in this work, it is preferable to build a WEN containing PDWEs.

Step 4a: Determination of pinch position

In order to construct a WEN scheme based on PDWEs, the pressure pinch point is needed. In reference to the problem table method of the HEN, the pressure pinch point of the WEN can be obtained by the following procedure:

Step 4.1: Divide pressure intervals;

After decreasing work source pressure by half of ΔP_{min} , and increasing work sink pressure by half of ΔP_{min} , the average pressure of each stream is obtained. Then by arranging all average pressures in descending order, the pressure region is divided into several intervals.

Step 4.2: Calculate work balance of each interval;

The delivered work values of sinks and sources are set to positive and negative respectively, which are added up to calculate the deficit work of each interval.

Step 4.3: Calculate cumulative work of each interval without work input;

The output work of each interval is calculated as the difference between input work and deficit work, and is equal to the input work of the next interval.

Step 4.4: Determine minimum work input of utility engineering;

When the output work is less than zero, external work needs to be introduced to ensure the sufficiency of work in each interval. Therefore, the minimum work input is set to the opposite value of the minimum of the surplus work output.

Step 4.5: Determine pressure pinch point.

In this step, cumulated work of each interval is calculated with the input of minimum external work, and the pinch point is observed where the output work is minimal. In addition, it should be noted that the necessity to set pressure intervals is dependent on the type of work exchanger. It is unnecessary for turbine-type WEs, as they are only subject to the value of indicated work, while it is inevitable for the PDWEs because the movement of piston requires $P_{HP,o} > P_{LP,t}$ and $P_{LP,o} > P_{HP,t}$.

Step 4b: Matching scheme based on turbine-type WEs

There are no pressure limits in the turbine-type WE, and even a high-pressure fluid can be pressurized by a low-pressure fluid. In some cases, the PDWE cannot be used in a transfer network and turbine is the only appropriate device, although energy transfer efficiency of turbine equipment is relatively low.

Planning a WEN scheme based on turbines does not require consideration of the pinch point. The primary concern is to match the amount of energy of the work sources and work sinks to maximize the quantity of recovered work. In addition, there is an upper limit to the matching number of streams when network stability is taken into account. The larger the number of other streams matching with a certain stream, the more susceptible the system is to be instable. In this work, the upper limit of the matching number is set as 2, which means one stream matches no more than two other streams. After establishing a WEN scheme based on turbines, we can proceed directly to Step 8.

Step 5: Second screening

The second screening is carried out when the pressure pinch point is obtained. Key streams that supply or need more indicated work are primarily investigated. If the minimum pressurize utility is positive in pinch analysis, the biggest work sources are the key streams. If the minimum pressurize utility is negative, the biggest work sinks are the key streams. Based on the restriction that streams do not match across the pinch, the target pressure of work source across the pinch should be set to pinch pressure. Considering the work exchange efficiency, the amount of practical recovered work W_{pr} can be calculated by multiplying W_{ind} with energy transfer efficiency η ,

$$W_{pr} = W_{ind} \cdot \eta \quad (2)$$

In addition, some streams must be boosted in advance to the pressure that is specified by rule (1) of Step 3 before matching, which is termed the pre-boost process. “Y” can then be subdivided into three situations, namely “N”, “M”, and “P”. “N” represents the stream that is unsuitable for matching after identification in the second screening, such as the stream with too little recovered work after the pre-boost process. “P” refers to the stream that can be directly applied by the PDWE. “M” indicates the stream that can be applied by the PDWE after pre-boosting.

Step 6: WEN matching scheme based on PDWEs

As shown in Fig. 3, work sources are listed on the left and work sinks are on the right, whereas the work exchangers are installed between them. The streams above the dotted line are above the pinch pressure. Due to the matching restrictions that work exchange is not applied across the pinch, the implementation of pinch point can simplify the superstructure of a WEN. Similar to an HEN, there are five principles that should be considered when applying pinch technology to build a WEN based on PDWEs, especially to match key streams:

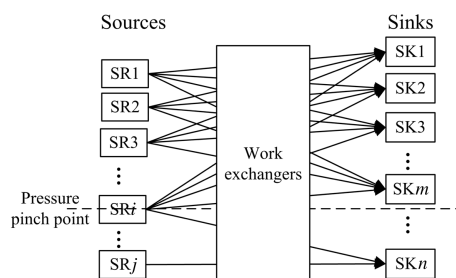


Fig. 3. Superstructure of a WEN with pressure pinch point.

- (1) Number of streams. In theory, pressure-relief devices should not be set above the pinch. This means that all HP streams achieve depressurization by transferring work to LP streams, i.e., $N_{HP} \leq N_{LP}$. Here, N_{HP} is the number of work sources with pressure higher than the pinch. N_{LP} is the number of work sinks above the pinch. Similarly, the booster should not be set below the pinch point, i.e., $N_{HP} \geq N_{LP}$ at the moment.
- (2) Volumetric flow rate. In order to ensure that the minimum pressure difference is at the pinch point, the streams around the pinch should meet the following rules: above the pinch, $V_{HP} \geq V_{LP}$; below the pinch, $V_{HP} \leq V_{LP}$.

The two principles (1) and (2) play guiding roles only near the pinch, and they are not strict requirements.

- (3) Maximize exchange load. In order to ensure the minimum number of work exchange units, each matching process should not be ended until the energy of one stream is used up.
- (4) Sequence rule. Streams are matched in the order of descending power supplied by work sources.
- (5) Matching numbers. One stream matches no more than two other streams.

After the key streams are matched, the remaining streams can be operated manually. Then a WEN based on PDWEs is generated.

Step 7: Construction of the final WEN

For streams which are weak and not suitable for the PDWE, the turbine-type WE is used to recover the rest pressure energy. Combining the characteristics of turbines and the PDWE, a final WEN can be constructed with the aim of achieving the maximum recovered work. This also can be adjusted based on equipment investment and production cost.

Step 8: Synthesis of the heat-work coupling transfer network

Considering the temperature variations of streams caused by heat transfer or throttling that occurs during the work exchange process, the operating conditions of the initial HEN need to be adjusted. The optimized heat-work coupling transfer network can then be formed.

4. Discussion Regarding the Application Problem

The two working fluids involving pressure energy transfer can be in liquid–liquid form, liquid–gas form, gas–liquid form or gas–gas form. Among these, the liquid–liquid form has the highest energy transfer efficiency (near 1.0) [26]. Moreover, work transfer in the liquid–liquid form abounds in a practical process. Therefore, this section and the subsequent case study mainly focus on application problems in the liquid–liquid form.

4.1. Equipment selection

The turbine-type WE is simple, runs smoothly, has few working condition limitations and is already applied in practical projects. However, the turbine-type WE has a lower energy transfer efficiency. In comparison, the PDWE has a higher energy transfer efficiency, even though it has a complex structure and more working condition constraints. Moreover, the successful application of PDWE in SWRO desalination indicates the possibility that the device could be similarly applied in the energy or chemical industry. Therefore, in terms of the higher efficiency and energy savings, a WEN matching scheme based on PDWE is the best choice. In specific cases, a hybrid matching scheme based on PDWE and the turbine-type WE, and even a pure matching scheme based on the turbine-type WE, is an alternative choice.

4.2. Throttling effects

For the PDWE, high pressure streams are depressurized transiently at the beginning of their flow in the cylinder, and the resulting phase change and cooling effects persist for an extremely short period of time. Therefore, no phase change is assumed in the recovery process, and the throttling effect can be ignored when establishing and optimizing a WEN because it has a little effect on the system.

4.3. Interaction analysis

4.3.1. Heat transfer effect

Since HP streams and LP streams with different temperatures flow through the cylinder alternately in the transfer process, the heat transfer phenomena will inevitably occur between the HP stream and the cylinder as well as between the cylinder and the LP stream. In addition, the pushing and mixing between two streams in the cylinder also leads to temperature variation of the streams. Fortunately, the amount of mixing is small according to the existing service experience of the PDWE in the SWRO system. As a result, the influence of temperature variation of the two streams will spread to the entire HEN. Therefore, the whole network must be adjusted. Considering that the heat transfer process in the PDWE is similar to a regenerative heat exchanger (or regenerator), this work uses the heat-transfer model of a regenerator [27] to approximately calculate the temperature change of the streams.

4.3.2. Pressure resistance of a HE

The maximum operating pressure of a heat exchanger in a heat-work coupling transfer network can be reduced by means of the work transfer process, or more specifically, by only adjusting its position from the front of a WE to the back. By adjusting the position, the pressures of the two streams in an HE can be closer to each other. The closer the two stream pressures are in the heat transfer process, the higher the resulting pressure resistance capacity of the heat exchanger. As a result, the material grade of the heat exchanger can be reduced.

4.4. Starting mode

Some mature experiences in the processing industry can be referenced to analyze the starting mode of the WEN. A pre-configured pump provides the original driving force to push a key work-sink stream. The power of the pump should meet the work demand of the stream to pressurize from original pressure to target pressure, and the priority selection of the driving system is a variable frequency motor.

The starting mode of the process can be forecasted as firstly building liquid circulation to make streams flow in an overall system. The pumps will start corresponding to key work sinks in order to boost the front part of the system. The work exchangers driven by the pressure differential between the front and the back of the system then begin to work. Meanwhile, the related gas streams and work-source streams should be under control when the system pressure rises. When the

system pressure reaches the normal state, all the work exchangers will start and the power of pre-configured pumps will simultaneously decrease. Then the system enters normal operating conditions.

5. Case Study

The rectisol process involves a gas purification technology that is widely used in the coal chemical industry. This process uses methanol as the sorption solvent and removes acidic gas in crude syngas using the selective absorption characteristics of a low temperature methanol solution. In this study, we analyze a typical rectisol process in a constructed synthetic ammonia plant with an annual output of 300 k tons. Since the HEN already exists, the design of the WEN and the optimization of the heat-work coupling transfer network in this system start from Step 2.

Step 2: Data extraction

Fig. 4 shows the basic process of the typical five-tower rectisol. It can be observed that the high-pressure methanol stream comes into contact with the process gas in the absorption tower (1) and absorbs acid gas like CO_2 and H_2S during the washing process. After that, one part of the stream flows out at the bottom of the absorption tower (1) and enters into the separator (S) after being depressurized to 1.75 MPa (G) by a pressure-reducing valve. Another part of the stream is extracted at the lower section of the tower, and is depressurized to 1.75 MPa (G) by a pressure-reducing valve. The volumetric flow rates of the two branch streams whose pressures significantly change are both larger than $100 \text{ m}^3 \cdot \text{h}^{-1}$ and can be deemed as two main work sources (SR1, SR2). The other two work sources (SR3, SR5) are the two liquid streams separated by the separator (S). The two streams both are depressurized to approximately 0.2 MPa (G) by pressure-reducing valves. The volumetric flow rates of these are relatively large, and a considerable amount of pressure energy can be recovered.

As shown in Fig. 4, the gas generated by the gas-liquid separator and the nitrogen-rich hydrogen gas coming from the liquid nitrogen wash mix together form the first work sink (SK1). Corresponding to the two pumps used to pressurize the extracting solutions from the knockout drum (KD) and the concentration tower (3), two work sinks (SK2, SK3) exist in the cycling system between the absorption tower (1) and the CO_2 desorption tower (2). The methanol circulating pump corresponding to the largest work sink (SK5) is the largest power consumer, and the methanol solution is pressurized by the pump from 0.05 MPa (G) to 6.4 MPa (G) before entering the absorption tower (1). There are two other work sinks (SK6, SK7) at the bottom and top of the methanol regeneration tower (4), which are used for the tower's liquid transportation and the top reflux, respectively. The basic data of the work sources and work sinks are shown in Table 1, where SR represents a work source and SK represents a work sink.

Step 3: Initial screening

Since this work mainly discusses the liquid-liquid matching process, and PDWE is not expected to be suitable for gas streams, SK1 is not taken into account as a work sink. According to stipulations of the initial screening, SR6, SK2, and SK7 are also not suitable for matching because their pressure energy is too small. Therefore, these four streams are marked as "N", and the rest of the streams that can be further investigated are marked as "Y". The initial screening results are displayed in column 7 in Table 1.

Step 4a: Determination of pinch position

As stated in Section 3, for the PDWE, the energy transfer efficiency is 0.94 and the pinch point pressure difference ΔP_{min} is set as 0.2 MPa. Based on the specific data analysis of the SR and SK with the problem table method used in pinch technology, the entire system is first divided into 13 intervals as shown in Fig. 5.

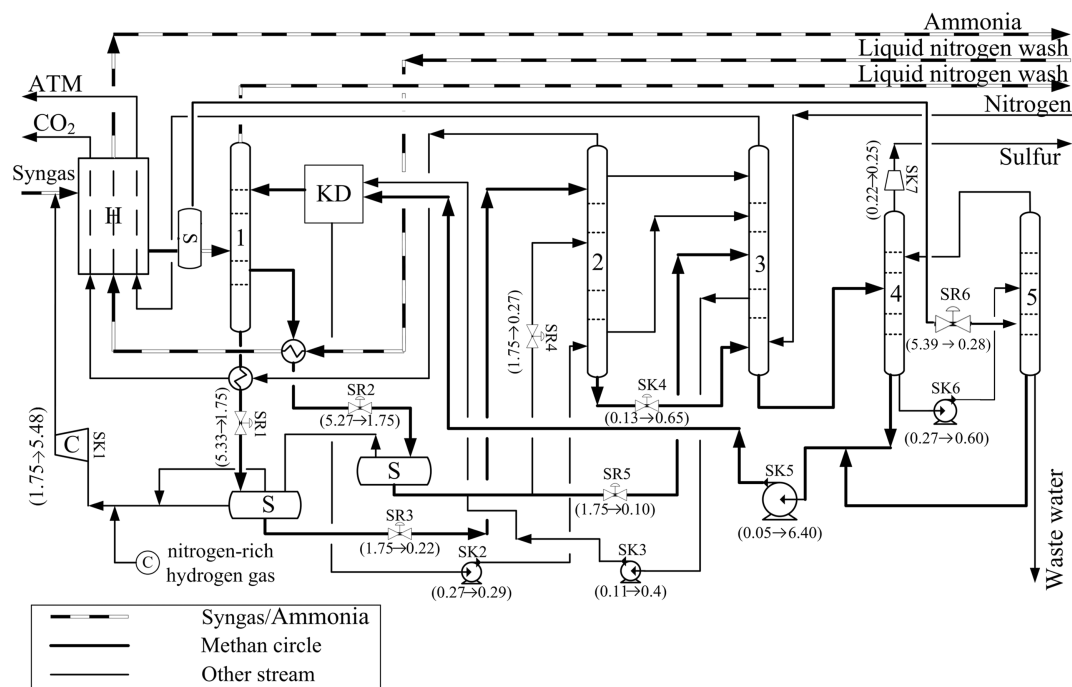


Fig. 4. Schematic diagram of typical five-tower rectisol process. 1—Absorption tower; 2—CO₂ Desorption tower; 3—Concentration tower; 4—Methanol Regeneration tower; 5—Methanol–Water Separator; C—Compressor; H—Heater; KD—knockout drum; S—Separator.

Deficit work refers to the work consumption of each interval, and a negative deficit work indicates that the pressure interval has surplus work. The computed deficit work of respective pressure intervals are shown in column 3 of Table 2. After calculating the work balance of each interval, the cumulative work of each pressure interval without input work from the outside are shown in columns 4 and 5 of Table 2. To make the cumulative output work of each pressure interval non-negative, external work with a minimum of 155.34 kW is introduced. Finally, the calculated results of recounting the output work of each pressure interval are shown in the last two columns of Table 2. Since all the pressure intervals' output work is not less than zero and the eleventh interval output work is zero, the pinch pressure is therefore determined to be 0.15 MPa.

Step 4b: Matching scheme based on turbine-type WEs

As previously stated, application of the turbine-type WE is not restricted by pressure range. A WEN based on the turbine-type WE is built mainly as a schematic comparison. According to the matching principle mentioned in Step 4b of Section 3, a turbine-type WEN matching scheme can be obtained as shown in Fig. 6. In the diagram,

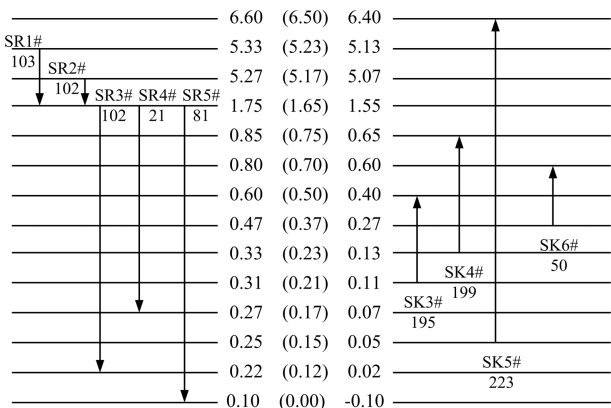


Fig. 5. Pressure interval division of a specific rectisol process.

“T” represents a turbine-type work exchanger, while the gray solid circle represents supercharging equipment such as a pump. The efficiency of a turbine-type WE is 0.75, and the amount of recovered work can be

Table 1
Basic data and screening results

Stream	P_o /MPa(G)	P_t /MPa (G)	Differential pressure/MPa	Flow/m ³ ·h ⁻¹	Indicated work/kW	Initial screening	Second screening
SR1	5.33	1.75	3.58	103	102.40	Y	P
SR 2	5.27	1.75	3.52	102	99.71	Y	P
SR 3	1.75	0.22	1.53	102	43.34	Y	M
SR 4	1.75	0.27	1.48	21	8.63	Y	M
SR 5	1.75	0.1	1.65	81	37.12	Y	M
SR 6	5.39	0.28	5.11	0.6	0.85	N	N
SK1	1.75	5.48	3.73	2719	–	N	N
SK 2	0.27	0.29	0.02	202	1.12	N	N
SK 3	0.11	0.4	0.29	195	15.71	Y	N
SK 4	0.13	0.65	0.52	199	28.74	Y	M
SK 5	0.05	6.4	6.35	223	393.24	Y	M
SK 6	0.27	0.6	0.33	50	4.58	Y	N
SK 7	0.22	0.25	0.03	10	0.08	N	N

Table 2
Computation sheet of problem table method

Pressure interval	Differential pressure/MPa	Deficit work/kW	Surplus work/kW		Cumulated work/kW	
			Input	Output	Input	Output
1	6.5–5.23	78.67	0.00	–78.67	155.34	76.67
2	5.17	2.00	–78.67	–80.67	76.67	74.67
3	1.65	17.60	–80.67	–98.27	74.67	57.07
4	0.75	4.75	–98.27	–103.02	57.07	52.32
5	0.7	3.03	–103.02	–106.05	52.32	49.29
6	0.5	14.89	–106.05	–120.94	49.29	34.40
7	0.37	16.72	–120.94	–137.66	34.40	17.68
8	0.23	16.06	–137.66	–153.72	17.68	1.62
9	0.21	1.19	–153.72	–154.91	1.62	0.43
10	0.17	0.21	–154.91	–155.12	0.43	0.22
11	0.15	0.22	–155.12	–155.34	0.22	0.00
12	0.12	–1.53	–155.34	–153.81	0.00	1.53
13	0	–2.70	–153.81	–151.11	1.53	4.23

calculated based on the basic data in Table 1. The calculated values of recovered work are listed in Table 3.

Step 5: Second screening

According to pinch technology, the minimum pressurizing utility is positive (155.34 kW). The two work-source streams with the largest indicated works (SR1 and SR2) are chosen as the key streams.

A second screening is carried out based on the pressure limit ($P_{HP,o} > P_{LP,t}$, $P_{LP,o} > P_{HP,t}$) and pinch point value (0.15 MPa). The pressures of key streams SR1 and SR2 are above the pinch, which are also between the original pressure and the target pressure of SK5 (Table 1). Therefore, SR1 and SR2 can be marked as “P” in the last column of Table 1. Since the original pressures of SR3 and SR5 are above the pinch, and the target pressure of SK4 or SK6 is within the pressure ranges of SR3 and SR5, SR3 and SR5 can be marked as “M” when they are matched with SK4 or SK6 with the aid of a certain supporting process. Similarly, the pressure range of SR4 is above the pinch, and it can be matched with SK4 or SK5 through a supporting process. Therefore, SR4 can be marked as “M”. It is found that the pressure interval of SK4 is across the pinch. Because the target pressure meets the matching requirements of pressure and volume flow, SK4 can be marked as “M” by pre-boosting the rest part below the pinch. The pressure range of stream SK5 is the largest (0.05 MPa–6.4 MPa) among the SK streams, and it can be matched with most of the SR streams. Therefore, SK5 is

Table 3
Recovered work from the turbine-type WE matching scheme

Exchange unit	The matching combination	Recovered work/kW
1	SR1 → SK5	77
2	SR2 → SK5	75
3	SR3 → SK4	29
4	SR4 → SK6	5
5	SR5 → SK3	16

marked as “M”. The original pressure of SK3 is 0.11 MPa which cannot be matched unless it is pressurized to 0.35 MPa in advance. This is because the target pressure of SR streams upon the pinch should be 0.25 MPa, and the driving pressure differential (0.1 MPa) is also required. The remaining energy of SK3 is only 2.7 kW, and SK3 is therefore marked as “N”. Similarly, the actual energy that can be transferred for SK6 is only 3.47 kW, and SK6 is also marked as “N”. The specific screening results are shown in the last column of Table 1.

Step 6: WEN matching scheme based on PDWEs

The matching scheme is divided into two parts that are above and below the pinch. Matching of the both parts proceeds respectively. According to the volumetric flow rate rule (2), the two streams cannot satisfy the volume flow requirement above and below the pinch simultaneously. Because the pinch pressure is small (only 0.15 MPa) without considering of the driving force requirement (0.1 MPa), the matching scheme below the pinch will not be considered in this case.

Based on the results of the second screening and its five rules, two key streams (SR1 and SR2) can be matched as follows: SR1 can be matched with the branch of SK5 (the corresponding flow is $113 \text{ m}^3 \cdot \text{h}^{-1}$, the original pressure and target pressure are 1.95 MPa and 5.05 MPa, respectively); SR2 can be matched with the other part of SK5 (the corresponding flow is $110 \text{ m}^3 \cdot \text{h}^{-1}$, the original and target pressures are 1.95 MPa and 5.05 MPa, respectively).

On the basis of the above results, there are 4 streams left that need to be matched: SR3, SR4, SR5 and SK4. Among the work sources, the work supplied by SR5 is closest to the energy needed by SK4, so SR5 is chosen to match with SK4. The matching scheme based on PDWEs is shown in Fig. 7. In the diagram, “M” indicates a PDWE unit with a pre-boosting process. However, it is observed that the direct matching, namely “P”, is not used widely and does not occur in this case. A gray solid circle in Fig. 7 indicates supercharging equipment such as a pump, and a

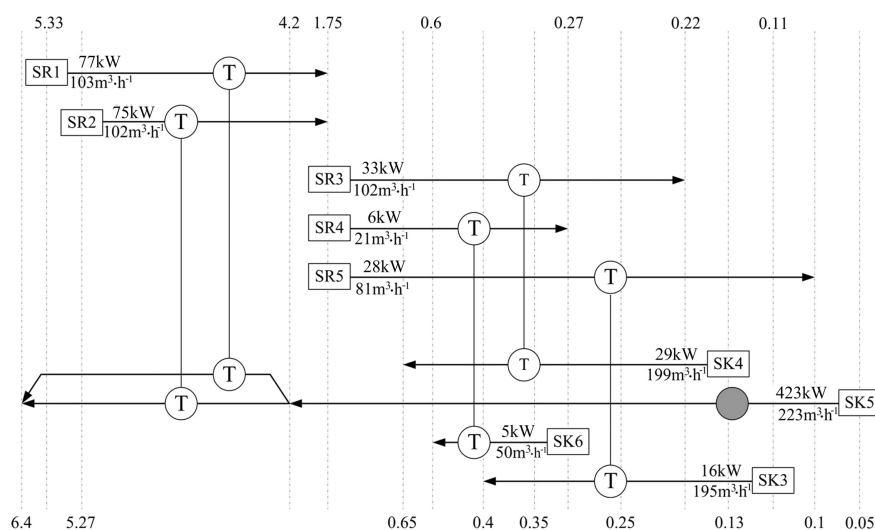


Fig. 6. Matching scheme based on turbine-type WEs.

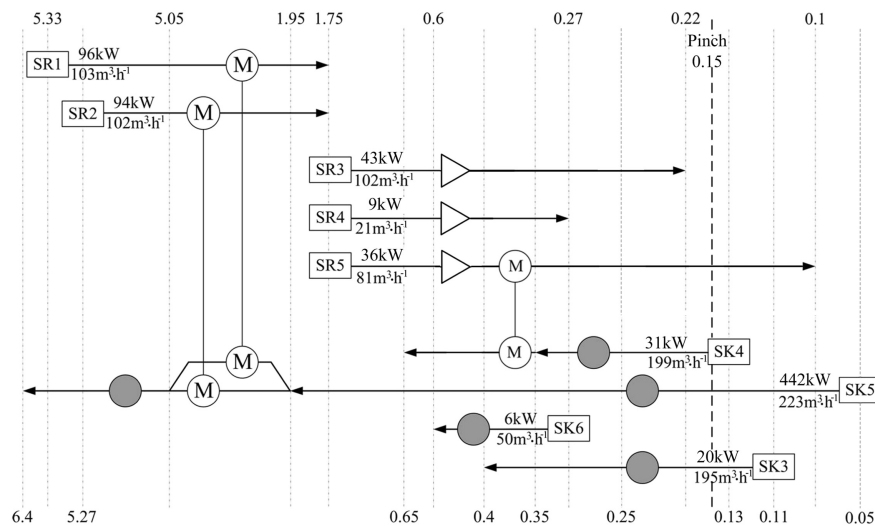


Fig. 7. Matching scheme based on PDWEs.

horizontal triangle indicates a pressure-reducing valve. According to the basic data and the energy transfer efficiency of the related equipment type, the amount of recovered work in each exchange unit can be obtained, and the specific values are shown in Table 4.

Table 4
Recovered work of the PDWE matching scheme

Exchange unit	The matching combination	Recovered work/kW
1	SR1 → SK5	96
2	SR2 → SK5	94
3	SR5 → SK4	19

Step 7: Construction of the final WEN

Considering the matching scheme based on the PDWE and characteristics of the turbine-type WE, the remaining SR streams that are not matched can be utilized by using pure turbines (T1, T2, T3 in Table 5) to recover their pressure to generate electricity. The initial WEN can then be achieved, and the required configuration is shown in Fig. 8. The specific quantity of recovered work of the initial WEN can be calculated. These results are shown in Table 5.

Step 8: Synthesis of the heat-work coupling transfer network

The incoming WEN will change the parameters of the original HEN. To obtain the final heat-work coupling exchange network, the influence of temperature changes caused by the WEN must be considered. Table 6

Table 5
Specific value of recovered work of the initial WEN

Exchange unit	The matching combination	Recovered work/kW
1	SR1 → SK5	96
2	SR2 → SK5	94
3	SR5 → SK4	19
T1	SR3	33
T2	SR4	6
T3	SR5	13
Total		261

shows the original pressure, temperature and flow rate data of the streams that pass through the three PDWE exchange units.

The heat-transfer calculation model in PDWEs is similar to that of the regenerator mentioned in Section 3. The detailed description of the equations is omitted here. The difference in heat transfer temperature differences can be calculated iteratively. The specific calculation results are shown in Tables 7, 8 and 9.

From Table 7, it can be observed that the most reasonable heat transfer temperature difference (Δtm) of unit 1 is approximately 50.0 °C, and the temperature changes of the two streams are both close to 7.8 °C.

From Table 8, it can be noted that the optimal heat transfer temperature difference (Δtm) of unit 2 is approximately 60.0 °C, and the temperature changes of the two streams are both 9.8 °C. The optimal tm of unit 3 is approximately 18.0 °C, and the stream temperature changes are nearly 2.2 °C, as shown in Table 9.

As the stream temperature changes are elucidated, we can adjust the operating conditions of the HEN and then generate the final heat-work coupling transfer network.

6. Conclusions

Global energy integration of an energy system has become more sophisticated and is not only a combination of heat energy, but also an integration of pressure energy. The specific integration method to building a heat-work coupling transfer network has been presented in this study. A systematic approach favors an HEN to be built first before a WEN is added to the energy transfer network, based on pinch technology. The final heat-work coupling transfer network is generated through fine-tuning the operation parameters of entire network. With the highest efficiency of energy transfer, the positive displacement type work exchanger is given priority to build a work exchange network. The study results show that pinch technology can be successfully used in a heat-work coupling transfer network. The influence of a positive displacement work exchanger on the energy transfer network in a coupling transfer system was investigated. The results showed that the effect of the phase change, throttle cooling and heat transfer could be neglected in the synthesis process. The theoretical analysis indicated that the approach was conceptually feasible. Finally, a case study of the typical rectisol process and the effect of added energy recovery is presented. The operability of the proposed method on the comprehensive energy transfer network is verified. This work provides a reference for constructing a more complex and larger energy synthesis network.

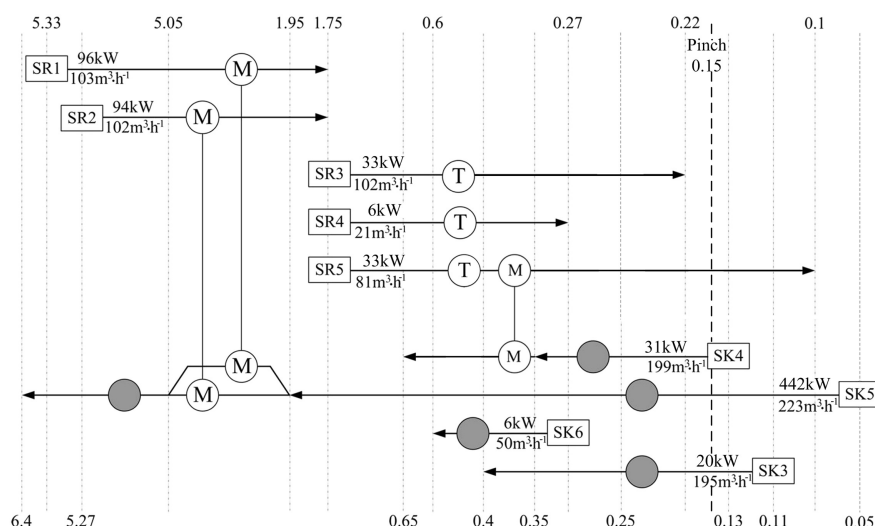


Fig. 8. Configuration of the initial WEN.

Table 6

Basic data of the three exchange units

Unit	Work Source	P_0/MPa	$T_0/^\circ\text{C}$	$F/\text{m}^3 \cdot \text{h}^{-1}$	Work Sink	P_0/MPa	$T_0/^\circ\text{C}$	$F/\text{m}^3 \cdot \text{h}^{-1}$
1	SR1	5.33	−16	103	SK5	0.05	42.3	223
2	SR2	5.27	−27	102	SK5	0.05	42.3	223
3	SR5	1.75	−31	81	SK4	0.13	−50.8	199

Table 7

Temperature change of work exchanger unit 1

$\Delta t_m/^\circ\text{C}$ (set value)	Q per cycle/kJ	SR1/ $^\circ\text{C}$	SK5/ $^\circ\text{C}$	$\Delta t_m'/^\circ\text{C}$ (calculated value)
48	3493	42.3/34.8	−8.5/−16	50.8
49	3566	42.3/34.6	−8.3/−16	50.6
50	3638	42.3/34.5	−8.2/−16	50.5
51	3711	42.3/34.3	−8.0/−16	50.3
52	3784	42.3/34.2	−7.9/−16	50.2

Table 8

Temperature change of unit 2

$\Delta t_m/^\circ\text{C}$ (set value)	Q per cycle/kJ	SR2/ $^\circ\text{C}$	SK5/ $^\circ\text{C}$	$\Delta t_m'/^\circ\text{C}$ (calculated value)
57	4329	42.3/33	−17.7/−27	60.0
58	4405	42.3/32.8	−17.5/−27	59.8
59	4480	42.3/32.7	−17.4/−27	59.7
60	4556	42.3/32.5	−17.2/−27	59.5
61	4632	42.3/32.3	−17/−27	59.3

Table 9

Temperature change of unit 3

$\Delta t_m/^\circ\text{C}$ (set value)	Q per cycle/kJ	SR5/ $^\circ\text{C}$	SK4/ $^\circ\text{C}$	$\Delta t_m'/^\circ\text{C}$ (calculated value)
16.3	918	−31/−33	−48.8/−50.8	17.8
17	957	−31/−33.1	−48.7/−50.8	17.7
18	1014	−31/−33.2	−48.6/−50.8	17.6
19	1070	−31/−33.3	−48.5/−50.8	17.5

Nomenclature

F	flow rate, $\text{m}^3 \cdot \text{h}^{-1}$
N	number of streams above the pinch
P	pressure, MPa
Q	quantity of heat transfer in a period per cycle, kJ
V	volume, m^3
W	work, kW
T	temperature, $^\circ\text{C}$
Δt_m	temperature difference (set value), $^\circ\text{C}$
$\Delta t_m'$	temperature difference (calculated value), $^\circ\text{C}$
η	energy transfer efficiency

Subscripts

HEN	heat exchanger network
HP	high pressure
HT	high temperature
ind	indicated work
LP	low pressure
LT	low temperature
o	original
PDWE	positive displacement-type work exchanger
pr	practical recovered work
t	target
WE	work exchanger
WEN	work exchange network

Acknowledgments

This work was supported by the National Natural Science Foundation of China (No. 20936004 and No. 21376187).

References

- [1] M. Ebrahim, A. Kawari, Pinch technology: An efficient tool for chemical-plant energy and capital-cost saving, *Appl. Energy* 65 (1) (2000) 45–49.
- [2] G.L. Liu, H. Li, X. Feng, C. Deng, Pinch location of the hydrogen network with purification reuse, *Chin. J. Chem. Eng.* 21 (12) (2013) 1332–1340.
- [3] Z.Y. Liu, Y.M. Li, G.L. Zhang, Y.Z. Yang, Simultaneously designing and targeting for networks with multiple resources of different qualities, *Chin. J. Chem. Eng.* 17 (3) (2009) 445–453.
- [4] I.S. Han, Y.H. Lee, C.H. Han, Modeling and optimization of the condensing steam turbine network of a chemical plant, *Ind. Eng. Chem. Res.* 45 (2) (2006) 670–680.
- [5] A. Aspelund, D.O. Berstad, T. Gundersen, An extended pinch analysis and design procedure utilizing pressure based exergy for subambient cooling, *Appl. Therm. Eng.* 27 (11) (2007) 2633–2649.

- [6] M.W. Shin, D. Shin, S.H. Choi, E.S. Yoon, C.G. Han, Optimization of the operation of boil-off gas compressors at a liquefied natural gas gasification plant, *Ind. Eng. Chem. Res.* 46 (20) (2007) 6540–6545.
- [7] M. El-Halwagi, D. Harell, H.D. Spriggs, Targeting cogeneration and waste utilization through process integration, *Appl. Energy* 86 (6) (2009) 880–887.
- [8] F.L. Del Nogal, J.K. Kim, S. Perry, R. Smith, Synthesis of mechanical driver and power generation configurations, Part 1: Optimization framework, *AIChE J.* 56 (9) (2010) 2356–2376.
- [9] F.L. Del Nogal, J.K. Kim, S. Perry, R. Smith, Synthesis of mechanical driver and power generation configurations, Part 2: LNG applications, *AIChE J.* 56 (9) (2010) 2377–2389.
- [10] C.Y. Cheng, S.W. Cheng, L.T. Fan, Flow work exchanger, *AIChE J.* 13 (3) (1967) 438–442.
- [11] O.M. Al-Hawaj, The design aspects of rotary work exchanger for SWRO, *Desalin. Water Treat.* 8 (1–3) (2009) 131–138.
- [12] J.X. Sun, Y. Wang, S.C. Xu, S.C. Wang, Energy recovery device with a fluid switcher for seawater reverse osmosis system, *Chin. J. Chem. Eng.* 16 (2) (2008) 329–332.
- [13] O.V. Sallangos, E. Kantilaftis, Operating experience of the Dhekelia seawater desalination plant using an innovative energy recovery system, *Desalination* 173 (1) (2004) 91–102.
- [14] W.T. Andrews, W.F. Pergande, G.S. McTaggart, Energy performance enhancements of a 950 m³/d seawater reverse osmosis unit in Grand Cayman, *Desalination* 135 (1) (2001) 195–204.
- [15] B. Peñate, J.A. De la Fuente, M. Barreto, Operation of the RO Kinetic® energy recovery system: Description and real experiences, *Desalination* 252 (1) (2010) 179–185.
- [16] J.Y. Mak, D. Heaven, Syngas purification in gasification-based ammonia/urea plants, *Ammonia Plant Saf. Relat. Facil.* 39 (1999) 319–331.
- [17] R.L. Stover, Seawater reverse osmosis with isobaric energy recovery devices, *Desalination* 203 (1) (2007) 168–175.
- [18] Y.W. Tan, B. Tan, Q. Wang, Progress in desalination project in China, *Technol. Water Treat.* 33 (1) (2007) 1–3 (in Chinese).
- [19] Y.L. Huang, L.T. Fan, Analysis of a work exchanger network, *Ind. Eng. Chem. Res.* 35 (10) (1996) 3528–3538.
- [20] M.S. Razib, M.M.F. Hasan, I.A. Karimi, Preliminary synthesis of work exchange networks, *Comput. Chem. Eng.* 37 (2012) 262–277.
- [21] G.L. Liu, H. Zhou, R.J. Shen, X. Feng, A graphical method for integrating work exchange network, *Appl. Energy* 114 (2014) 588–599.
- [22] J.Q. Deng, J.Q. Shi, Z.X. Zhang, X. Feng, Thermodynamic analysis on work transfer process of two gas streams, *Ind. Eng. Chem. Res.* 49 (24) (2010) 12496–12502.
- [23] V.C. Onishi, M.A. Ravagnani, J.A. Caballero, Simultaneous synthesis of heat exchanger networks with pressure recovery: Optimal integration between heat and work, *AIChE J.* 60 (3) (2014) 893–908.
- [24] Y.D. Zozulyak, Y.L. Levashov, V.T. Novatsky, Precision setup for fluid pump efficiency testing, *Heat Transf. Res.* 28 (7) (1997) 499–502.
- [25] I.B. Cameron, R.B. Clemente, SWRO with ERI's PX pressure exchanger device—a global survey, *Desalination* 221 (1) (2008) 136–142.
- [26] J.Q. Deng, L. Ma, X. Feng, Work recovery efficiency of work exchange in chemical process, *J. Chem. Ind. Eng.* 62 (11) (2011) 3017–3023.
- [27] H.T. Cui, F. Yang, Thermal-storage Technology and Application, Chemical Industry Press, Beijing, 2004 (in Chinese).