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Simultaneously Retrofit of Heat Exchanger Networks and Towers for a Natural Gas Purification Plant

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As an essential part of Heat Integration, the heat exchanger network (HEN) plays a vital role in large-scale industrial fields. The optimisation of HEN can increase energy efficiency and considerably save the operating and investment cost of the project. This study presents a novel approach for simultaneous optimisation of plant operating variables and the HEN structure of an existing natural gas purification process. The objective function is the total energy consumption of the studied process. A two-stage method is developed for optimisation. In the first stage, a particle swarm optimisation (PSO) algorithm is developed to optimise variables including tower top pressure, tower bottom pressure, and reflux ratio on the HEN, thereby changing the initial temperatures of cold and hot streams in the HEN. In the second stage, a shifted retrofit thermodynamic grid diagram (SRTGD)-based model and the corresponding solving algorithm was applied to retrofit the HEN. The case study shows that the optimal operating conditions of towers and temperature spans of heat exchangers can be solved by the proposed method to reduce the total energy consumption. The case study shows that the total energy consumption is reduced by 41.5 %.

1. Introduction

Heat Integration is an important method to achieve energy-saving in the process industry. Many streams need to be cooled or heated to achieve their target temperatures. For example, the raw materials need to be preheated to a certain temperature before entering the reactor, and the products may need to be cooled before entering the separation unit or storage unit. By optimising the HEN to reasonably match the hot stream and cold stream in the system, it can make full use of the heat of hot streams, increase system energy recovery, improve energy utilisation efficiency, and reduce energy consumption (Klemeš et al., 2020).

There are many heating and cooling streams in the natural gas purification process. The operating variables of the tower have a greater impact on the purification efficiency and energy consumption of the natural gas purification plant. For high-sulphur natural gas, it needs to be purified to meet the requirements of commercial gas. The energy consumption accounts for about 30 % of the total energy consumption of the entire sulfur-containing natural gas development process (Zhou et al., 2019). It is very necessary to optimise the HEN and the operation of a tower of the natural gas purification process to reduce energy consumption.

Pinch Analysis has been widely used in the chemical industry and continuously developed. Linnhoff et al. (1983) found the pinch point by determining the minimum heat transfer temperature difference and used this method to determine the minimum utility usage. Lakshmanan et al. (1996) proposed a Retrofit Thermodynamic Diagram (RTD), which displays the information of streams, utilities, heat exchangers and the relationship between them. Yong et al. (2014) developed a Shifted Retrofit Thermodynamic Diagram (SRTD), which is a modification of RTD combined with thermodynamic feasibility expression and minimum allowable temperature difference. Yong et al. (2015) used heat capacity flow rate and temperature as ordinate and abscissa to establish Shifted Retrofit Thermodynamic Grid Diagram (SRTGD), which is an extension of the SRTD. Wang et al. (2020a) considered

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heat exchanger types in the HEN retrofit by developing an extended grid diagram-based tool. Kang et al. (2016) developed a method based on the Temperature-Heat (T-Q) diagram for the design of large-scale HENs. Wan Alwi and Manan (2010) presented the Stream Temperature versus Enthalpy Plot (STEP), which shows the Pinch Points, energy targets and the maximum heat allocation. Gadalla (2015) proposed a HEN retrofit and energy integration graphical method based on the comparison chart of the process heat flow temperature and the process cold flow temperature. Besides the widely used Pinch Analysis, another branch for solving HEN synthesis and the retrofit problem is mathematical programming. Papoulias et al. (1983) proposed a linear model to determine the energy target of the HEN and a mixed-integer linear programming model to determine the number of heat exchange matching. Akos and Friedler (2020) developed a P-graph based method to optimise the HEN. Potential heat exchanger networks were generated first, and then the optimum was determined according to the total annualised cost. Wang et al. (2020b) developed a method for HEN retrofit by a shifted retrofit thermodynamic grid diagram-based model and a two-stage approach.
Previous works focused only on the optimisation of HENs. However, for the studied problem, the operation of the tower affects the inlet and outlet temperatures of the streams, and the design of the HEN affects the tower operation. The operation of the tower and the design of the HEN should be optimised simultaneously.
To achieve this purpose, firstly, Aspen HYSYS (Aspen Technology, 2021) is applied to simulate the natural gas purification process. Aspen HYSYS has a powerful process simulation function, and many designers use it to simulate the process flow. Saadi et al. (2019) used Aspen HYSYS to develop a Liquefied Petroleum Gas (LPG) unit production, which is used to obtain necessary data for exergy analysis. Qeshta et al. (2015) used Aspen HYSYS to establish a model for the desulphurisation process of liquefied petroleum gas and performed a parameter sensitivity analysis of the model. By optimising the operation of the natural gas purification process, the total energy consumption of the purification plant can be reduced. In this work, a two-stage method is developed to reduce the total energy consumption. In the first stage, a PSO algorithm is developed to optimise variables, including tower top pressure, tower bottom pressure, and reflux ratio on the HEN, and changing the initial values of cold flow and heat flow in the HEN. In the second stage, a shifted retrofit thermodynamic grid diagram-based model with the corresponding solving approach was selected and applied to retrofit the HEN.
The contributions of this research are as follows:

- A two-stage method is developed for the optimisation of tower operating variables and the HEN of a natural gas purification plant.
- The developed method considers the trade-off between the utility cost and the new heat exchanger investment cost.
- This method can be widely used in industrial heat exchange networks to reduce system energy consumption.

The remaining sections of the paper are organised as follows. A two-stage method to optimise the total energy consumption of the natural gas purification plant is introduced in Section 2. In Section 3, a case is optimised to verify the method proposed in this study. Section 4 summarises the conclusions.

2. Method

The natural gas purification plant mainly includes a gas sweetening unit (GSU), dehydration unit (DU). In the GSU, the natural gas enters the bottom of the desulphurisation tower and flows to the top while fully contacting with the methyldiethanolamine to remove H_2S and part of CO_2 in the natural gas. After desulphurisation, the wet purified gas enters the DU and contacts the dehydrated water solution to remove the water carried out from the desulphurised solution. Figure 1 shows the process of the natural gas purification plant.

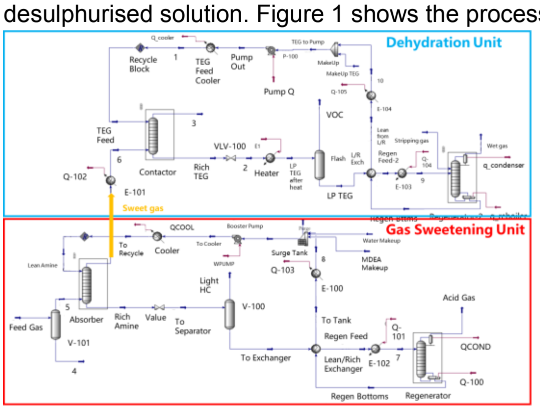

Figure 1: Process model diagram established by Aspen HYSYS

In this section, the PSO algorithm and MILP formulation are used to establish an optimisation model for the adjustment of the operation of the tower and the HEN. The overall framework is shown in Figure 2. The detailed steps are as follows:

Step (i) According to the field data of the purification plant, Aspen HYSYS is used to simulate the process.

Step (ii) The data of ASPEN HYSYS is transmitted based on the component object model (COM), and the PSO algorithm is established by MATLAB to optimise the operation of the tower in the purification plant. The operation of the tower is obtained through the COM interface and is optimised by the PSO algorithm. The optimised tower operation is then input into Aspen HYSYS for process calculation through the COM interface. The calculation result is used to judge whether the optimised plan meets the temperament condition of the product gas. If it is satisfied, the p-best and the g-best, which are two criteria for PSO, are updated. If it is not satisfied, a larger value is added as the penalty. Then it is judged whether the termination condition is met. If it is met, go to step (iii). If not, the particle is updated for the next iteration. The objective function is the total energy consumption of the purification plant.

Step (iii) The cold flow, heat flow, heat exchanger and other data of the ASPEN HYSYS model from the optimisation results of step (ii) were extracted and input into the developed MILP model which is based on the structure of the SRTGD.

Step (iv) The inlet and outlet temperatures of each heat exchanger based on the structure obtained via the MILP model were optimised by the PSO algorithm. The temperature of the heat exchangers in the solution of the MILP model is input into the PSO algorithm as a particle in the initialisation. The HEN is judged whether its structure and operation remain unchanged. If the structure and operation of the HEN are changed, go back to step (i) for a new round of iteration. If not, the best HEN retrofit plan is determined.

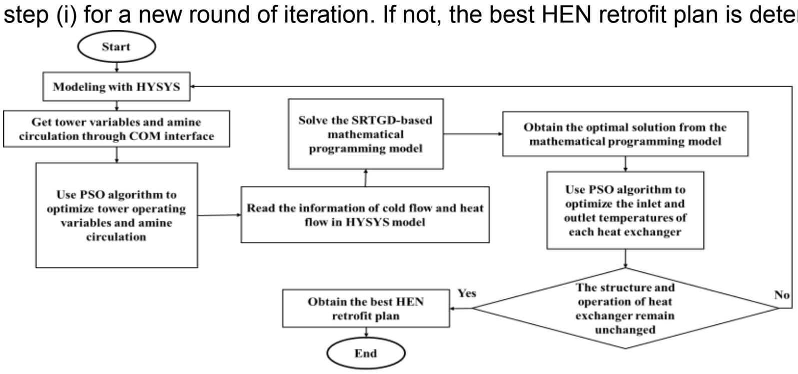

Figure 2: Flowchart of the proposed simultaneous optimisation method

PSO algorithm is an evolutionary algorithm based on bird colony intelligence. The various agents in the PSO cooperate with each other to better adapt to the environment, which has the advantages of fast convergence and good robustness. The PSO algorithm has been applied to this paper due to its strong ability to search for the optimal results in real numbers and to avoid premature convergence to a local optimum.

Step (a) Initialization

In this algorithm, the operation of the tower is treated as particles and initialised within the range of reasonable range. Individual particles can only change within a reasonable range. The population size is set as 20 in this case.

$$\begin{aligned} &0.8 \le x_1 \le 2 \\ &100 \le x_2 \le 120 \\ &130 \le x_3 \le 150 \\ &90 \le x_4 \le 100 \end{aligned} \tag{1}$$

where x_1 is the reflux ratio at the top of the tower in GSU; x_2 is the pressure at the top of the tower in GSU, kPa; x_3 is the pressure at the bottom of the tower in GSU, kPa; x_4 is the pressure at the top of the tower in DU, kPa. The x_1, x_2, x_3, x_4 mentioned above are all optimisation variables.

Step (b) Conditional judgment

The H_2S concentration and the CO_2 concentration in purified gas after treatment should be less than 6 mg/m^3 and 2 %(mol). The water dew point of the product gas should be less than -15 °C in winter and less than -10 °C in summer. If it meets the standard, read the data in the Aspen HYSYS model to calculate the fitness function. Otherwise, the penalty value (maximum value) is assigned to the fitness value of the individual to eliminate the individual in the evolution process.

$$SweetGas_{H_2S} \leq 6$$
$$SweetGas_{CO_2} \leq 2 \qquad (2)$$
$$ProductGas_{H_2O} \geq -15$$

where $SweetGas_{H2S}$ is the H_2S concentration of product gas, mg/m^3; $SweetGas_{C2O}$ is the CO_2 concentration of product gas, %(mol); $ProductGas_{H2O}$ is the water dew point of the product gas, °C.
Step (c) Evaluate fitness
The total energy consumption of cold and heat flows in the ion of the purification plant is used as the fitness function. The model established by ASPEN HYSYS can show the energy consumption of heating furnaces, circulating pumps, cooler and other devices in detail. The total energy consumption of the purification plant is obtained by extracting the energy consumption value of the device and summing it. The objective function is shown in Eq(3).

$$Energy = \sum_{i=1}^{n} E_i(x) \qquad (3)$$

where Energy is the total energy consumption of the purification plant, kJ, $E_i(x)$ is the energy consumption of each device in the purification plant extracted from the ASPEN HYSYS, kJ.
Step (d) Update velocity and position
Every particle has a speed and position. In each iteration, change the speed and position according to Eq(4) and Eq(5).

$$v_{i,t+1} = v_{i,t} + c_1 r_1 (pbest_{i,t} - x_{i,t}) + c_2 r_2 (gbest_{i,t} - x_{i,t}) \qquad (4)$$

$$x_{i,t+1} = x_{i,t} + v_{i,t+1} \qquad (5)$$

where $v_{i,t}$ is the velocity of particle i at the tth iteration; $pbest_{i,t}$ is the personal historical best position of particle p at the tth iteration, $gbest_{i,t}$ is the global historical best position of all particles at the tth iteration. c_1 and c_2 are acceleration coefficients. In this paper, they are both set as 2. r_1 and r_2 are two uniformly generated random numbers in the range [0, 1]. $x_{i,t}$ is the position of particle i at the tth. The velocity of a particle is updated according to Eq(4). The position of the particle when at iteration t+1th is equal to the position of the particle when the iteration is t+1$^{th;}$ add the velocity of the particle when the iteration is t+1th. With the velocity and position updating, the constraints for each particle will be checked to ensure that the retrofit plan is feasible.

3. Case study

An Aspen HYSYS model of the purification plant is developed according to the field data. The Aspen HYSYS model of the studied purification plant is shown in Figure 1. The HEN information is extracted by the purification plant process established above. The stream data is shown in Table 1. This HEN has five hot streams and three cold streams. The Shifted Pinch is at T* of 23 °C, and the ΔT_{min} is 5 °C. The grid diagram of the existing HEN is shown in Figure 3, along with the heat capacity of each stream. The existing HEN has two heat exchangers. One of the heat exchangers connects stream 1 and stream 5, and the other heat exchanger connects stream 3 and stream 8. Utilities are located on each stream to provide cold and heat. The existing HEN only has one recovery heat exchanger and a very low degree of heat recovery. This determines the high potential for utility savings by retrofit.

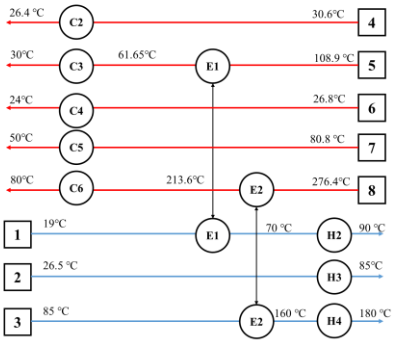

Figure 3: Grid Diagram of the HEN

Table 1: Stream Data of the HEN

Stream	T_S (°C)	T_T (°C)	CP (kW/°C)	h (kW/m^2·°C)
1	18.86	90	10.78	1.68
2	26.45	85	3.87	1.16
3	85	180	4.43	1.15
4	30.67	26.38	9.68	1.52
5	108.90	30	10.38	1.51
6	26.42	24	29.79	0.20
7	80.80	50	3.84	1.17
8	276.39	80	4.69	1.08

Note: T_S is the supply temperature, (°C); T_T is the target temperature, (°C); CP is the heat-capacity flow rate, (kW/°C); and h is the heat transfer coefficient, (kW/m^2·°C)

Following the proposed method of simultaneous optimisation of the operation of the tower and HEN, the changes in the operation of the tower are shown in Table 2, and the retrofit design results are shown in Figure 4.

Table 2: The operating variables of on-site and optimised results

The operation of the tower	On-site	Optimum
the reflux ratio at the top of the tower in GSU	1	0.8
the pressure at the top of the tower in GSU, kPa	120	107.6
the pressure at the bottom of the tower in GSU, kPa	130	130
the pressure at the top of the tower in DU, kPa	101	96.96

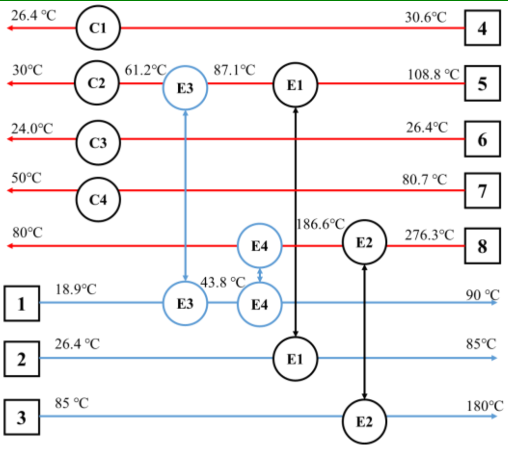

Figure 4: Grid Diagram of the HEN retrofitted by the method

It can be found from the results that the optimised operations of the tower have been adjusted to provide better initial conditions for the optimisation of the HEN. In the retrofitting of HEN, two new heat exchangers were added, and the initial heat exchanger was modified to a certain extent. After the HEN transformation, three heaters and one cooler were removed. Stream 5 and stream 8, in which temperature and energy are very high, need to be cooled by the cooler to exchange heat with the cold stream.

Table 3: Comparison of the optimised and on-site results of the case

Case	On-site	Optimised
Annualised hot utility cost, $/y	40,345	18,262
Annualised cold utility cost, $/y	23,149	0
Annualised investment cost, $/y	0	17,735
Total energy consumption, GJ/h	10.6	6.2

The comparison of the optimised and on-site results of the case is shown in Table 3. In the initial situation, the total energy consumption of the purification plant is 10.6 GJ/h. After the simultaneous optimisation of the operation of the tower and HEN, the total energy consumption of the purification plant is reduced to 6.2 GJ/h. The overall heat exchange efficiency of the HEN is improved, and the utility cost is reduced through the matching of cold flow and heat flow.

4. Conclusions

Through the analysis of the operation of the tower, it shows that the operation of the tower has a greater impact on the initial temperatures of the HEN. The optimised results show that the proposed method, which simultaneously optimised the operation of the tower and HEN, was demonstrated successfully. The method is based on the process simulation model established by Aspen HYSYS and a two-stage algorithm. The objective function of the first stage is to minimize total energy consumption and the second is to minimize annual cost.
This method realises the overall optimisation of the natural gas purification plant. Considering the influence of the operation of a tower on the initial temperature of the HEN, the collaborative optimisation of the operation of the tower and HEN can be realised. This method can help users determine the joint adjustment of the operation of the tower and HEN to achieve the minimum total energy consumption and annual cost. It can also introduce the designer's experience through fixed variables, manual intervention in the optimisation process.
Through the study of field cases, the effectiveness of this method in assisting transformation decision-making is verified. The results show that through the application of this method, the total energy consumption is reduced by 41.5 %. Future research should focus on the application of other factories and develop a more general applicable factory-wide optimisation method.

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References

Aspen Technology, Inc, 2021, Aspen HYSYS <www.aspentech.com/en/-/media/aspentech/home/resources/faq-documents/pdfs/at-04066-faq-acid-gas-removal.pdf> accessed 30.06.2021.
Gadalla M.A., 2015. A new graphical method for Pinch Analysis applications: HEN retrofit and energy integration, Energy, 81, 159-174.
Kang L., Liu Y., Jiang N., 2016, Synthesis of large-scale HENs using a T-Q diagram method. The Canadian Journal of Chemical Engineering, 94(10), 1955-1964.
Klemeš J.J., Wang Q.W., Varbanov P.S., Zeng M., Chin H.H., Lal N.S., et al, 2020, Heat transfer enhancement, intensification and optimisation in HEN retrofit and operation, Renewable and Sustainable Energy Reviews, 120, 109644.
Linnhoff B., Hindmarsh E., 1983, The pinch design method for heat exchanger networks, Chemical Engineering Science, 38(5), 745-763.
Lakshmanan R., Banares-Alcantara R., 1996, A Novel Visualization Tool for Heat Exchanger Network Retrofit, 35(12), 4507-4522.
Orosz Á., Friedler F., 2020, Multiple-solution heat exchanger network synthesis for enabling the best industrial implementation, Energy, 208, 118330.
Papoulias S.A., Grossmann I.E., 1983. A structural optimisation approach in process synthesis—II: Heat recovery networks, Computers & Chemical Engineering, 7(6), 707–721.
Qeshta H.J., Abuyahya S., Pal P., Banat F., 2015, Sweetening liquefied petroleum gas (LPG): Parametric sensitivity analysis using Aspen HYSYS, Journal of Natural Gas Science and Engineering, 26, 1011-1017.
Saadi T., Jeday M.R., Jaubert J.N., 2019, Exergetic analysis of an LPG production plant using HYSYS software, Energy Procedia, 157, 1385-1390.
Wan Alwi S.R., Abdul Manan Z., 2010, STEP—A new graphical tool for simultaneous targeting and design of a heat exchanger network, Chemical Engineering Journal, 162(1), 106-121.
Wang B., Klemeš J.J., Varbanov P.S., Chin H.H., Wang Q.W., Zeng M., 2020a, HEN retrofit by a shifted retrofit thermodynamic grid diagram-based model and a two-stage approach, Energy, 198, 117338.
Wang B., Klemeš J.J., Varbanov P.S., Zeng M., 2020b, An Extended Grid Diagram for Heat Exchanger Network Retrofit Considering Heat Exchanger Types, Energies, 13(10), 2656.
Yong J.Y., Varbanov P.S., Klemeš J.J, 2014, Shifted retrofit thermodynamic diagram: a modified tool for retrofitting heat exchanger networks, Chemical Engineering Transactions, 39, 97-102.
Yong J.Y., Varbanov P.S., Klemeš J.J., 2015. Heat exchanger network retrofit supported by extended Grid Diagram and heat path development, Applied Thermal Engineering, 89, 1033-1045.
Zhou J., Peng J., Liang G., Deng T., 2019, Layout optimisation of tree-tree gas pipeline network, Journal of Petroleum Science and Engineering, 173,666-680.