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Optimization of hydrogen distribution network considering pressure and heat recovery

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Abstract

Hydrogen is an important resource in chemical processes. In the hydrogen network, many units are operating at high temperature and pressure, which leads to a large energy change of hydrogen streams. However, the recovery of heat and work in the hydrogen flows has seldom been studied together with the optimization of hydrogen network. It is obviously that the reuse of heat and work energy will raise the effective utilization rate of energy. The recovery of heat could be realized by heat exchangers. The recovery of work will be realized by rotary work exchangers, which are composed of several compressors and turbines with the same shaft. A state space superstructure is adopted to handle all the variables. The mathematical model is built based on exergoeconomic analysis considering both energy and economic factors. The optimization problem will be a mixed integer nonlinear programming (MINLP) problem. The existing algorithms will be improved. A typical refinery hydrogen network is studied as an example. The state space superstructure, exergoeconomic analysis and proposed algorithm could solve the problem competently. The consideration of pressure and heat recovery could reduce the energy consumption and economic cost simultaneously.

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Keywords: Hydrogen network; Heat recovery; Work recovery; Exergoeconomic analysis; Global optimization algorithm

1. Introduction

With the rapid development of the world economy and industry, the consumption of fossil fuels is increasing sharply. The utilization of fossil fuels leads to many serious problems, such as energy crisis, greenhouse effect, environmental pollution and so on. As an important chemical material, hydrogen could also be used as an alternative energy source. With the increasing requirement on oil quality and rigorous environmental policies, the refineries should raise the capacity of hydrotreating to cover the increasing

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consumption of hydrogen. Therefore, the efficient use of hydrogen and the optimization of hydrogen distribution network are of important significance for refineries.

Simpson [1] first addressed the major role of hydrogen management in the design and operational considerations of the refinery in 1984. There are two main methods to optimize the hydrogen distribution network, which are pinch analysis [2] and mathematical programming method [3]. The optimization of hydrogen distribution network considering hydrogen compression process has been studied a lot. Wu et al. [4] proposed the exergy objective to express hydrogen consumption and compression power on a common basis. They adjusted the number of compressors manually after the calculation. However, the optimization of compressor positions could also be determined by mathematical programming [5].

In a refinery, the operating temperature and pressure of hydrogen flows are often very high, which leads to large temperature and pressure differences between the hydrogen sources and hydrogen sinks. Therefore, it is important to consider the temperature and pressure of hydrogen flows in the hydrogen distribution network. This paper will focused on the optimization of hydrogen distribution network considering pressure and heat recovery. The superstructure, mathematical model and algorithm will be studied. A case study will be carried out to prove the suitability of the whole optimization procedure.

2. Problem Statement

The most important basic utilities in refineries are heat, work and hydrogen, which should be optimized simultaneously for a globally optimal solution. A state space superstructure for integrated heat, mass and work exchange network [6] is adopted in this study. The proposed superstructure by Dong et al. [6] could easily handle all the variables. Different from traditional hydrogen distribution network, the heat and work recovery will also be incorporated in the optimization. Each hydrogen source with the given flow rate (F_i), pressure (p_i), temperature (T_i) and purity (y_i), will be allocated to hydrogen sinks. Each hydrogen sink has the limits to inlet purity (y_i^{min}), flow rate (y_i^{min}), temperature (T_j) and pressure (p_i).

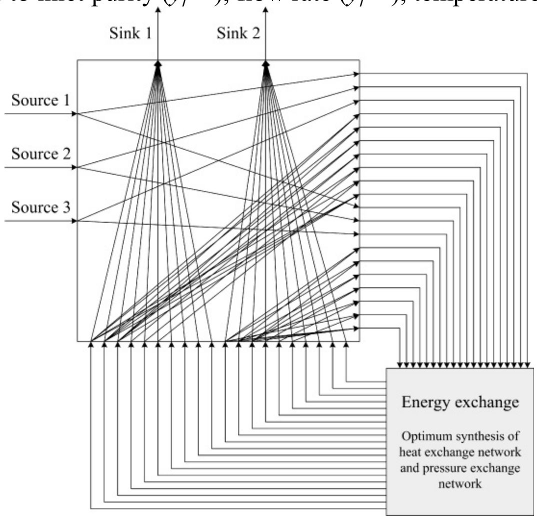

Fig. 1. State space superstructure [6]

The recovery of heat will be realized by heat exchangers, and the recovery of work will be realized by work exchangers. A typical work exchanger contains an electric motor, several compressors and turbines with the same shaft. The work from depressurized hydrogen flows will be transferred to pressurized flows as shaft power. The exergy of hydrogen distribution network will be analyzed. The chemical exergy reveals the flow rate and purity of hydrogen flows, while the physical exergy stands for the temperature and pressure. The exergoeconomic analysis is carried out by considering both exergy and economic costs. The objective will be minimizing the total annual economic cost per unit exergy of hydrogen sinks. The optimization will be a nonconvex mixed integer nonlinear programming (MINLP) problem.

3. Mathematical Model

In the hydrogen distribution network, there are *m* hydrogen sources and *n* hydrogen sinks with respective flow rate, purity, temperature and pressure. Based on exergoeconomic analysis and the superstructure shown in Fig. 1, mathematical model is developed to solve the problem.

According to the exergoeconomic analysis, the objective is to minimize the annualized economic cost per unit exergy of hydrogen sinks (c_{out}).

$$\min c_{\text{out}} = \min\left(C/E_{\text{out}} + c_{\text{in}}/\eta_e\right) \quad (1)$$

The annualized economic cost C could be calculated by the capital cost C_e and operating cost C_o.

$$C = C_e/x + C_o \quad (2)$$

The exergy of hydrogen sink flows E_{out} can be calculated by Eq. (3).

$$E_{\text{out}} = E_{\text{in}} - E_{\text{loss}} \quad (3)$$

$$\eta_e = E_{\text{out}}/E_{\text{in}} \quad (4)$$

The exergy of hydrogen flow is the summation of chemical exergy and physical exergy.

$$e_i = e^0_{\text{H}_2} + \left(h_i - h^0_{\text{H}_2}\right) - T_0\left(s_i - s^0_{\text{H}_2}\right) \quad (5)$$

$$E_{\text{in}} = \sum_{i=1}^{m}\left(e_i \sum_{j=1}^{n} F_{i,j}\right) + W_{\text{in}} + Q_{\text{in}} \quad (6)$$

The exergy loss mainly takes place in the heat and pressure exchange process and mixing process, which is shown in Table 1. The constraint equations of flow rate, purity, temperature and pressure are shown in Table 2.

Table 1. Constraint equations of exergy loss

Item	Constraint equation	
Total exergy loss	$E_{\text{loss}} = E_{\text{loss,m}} + E_{\text{loss,t}} + E_{\text{loss,p}}$	(7)
Exergy loss in mixing process	$E_{\text{loss,m}} = T_0 \Delta S = -T_0 R \sum_l \left(n_l \ln y_l\right)$	(8)
Exergy loss in heat exchange process	$E_{\text{loss,t}} = T_0 Q_{\text{H}}\left(1/T_{\text{Hm}} - 1/T_{\text{Lm}}\right)$	(9)
Exergy loss in pressure exchange process	$E_{\text{loss,p}} = \sum\left[\left(1-\eta_{\text{p}}\right)W_{\text{p}}\right] + \sum\left(p_{\text{loss}} F/\rho_{\text{H}_2\text{O}}\right)$	(10)

Table 2. Constraint equations of hydrogen flows

Item	Constraint equation	
Hydrogen source	$\sum_{j=1}^{n} F_{i,j} \le F_i$	(11)
Hydrogen sink	$F_j^{\min} \le \sum_{i=1}^{m} F_{i,j}$	(12)
Purity	$\sum_{i=1}^{m}\left(F_{i,j} y_i\right) \Big/ \sum_{i=1}^{m} F_{i,j} \le y_j^{\max}$	(13)
Temperature	$T_{i,j} = T_j$	(14)
Pressure	$p_{i,j} = p_j$	(15)

The interaction between temperature and pressure of hydrogen flow could be calculated by Peng-Robinson (PR) equation as Eq. (16) shown. The coefficients could be obtained in the literature [7].

$$p = RT/(V-b) - a(T)/[V(V+b)+b(V-b)] \quad (16)$$

4. Algorithm

There are so many variables in the mathematical model. Almost all the variables have interaction between each other, which leads to many bilinear terms. The algorithm, which is efficient to deal with bilinear terms, should be carried out to solve the optimization problem of hydrogen distribution network considering pressure and heat recovery.

Now the most efficient algorithm to treat bilinear terms is direct partitioning methodology [8]. The equal section is adopted in the partitioning process. However, golden section could be more efficient than equal section. Branch and bound (BB) algorithm is thought to be an efficient way to find out the optimal network structure. Therefore, a hybrid parallel algorithm composed by BB algorithm, partitioning methodology and golden section method is proposed in this paper. A case study from literature [6] is carried out. Both partitioning methodologies with equal section and golden section are studied. The result in Fig. 2 shows that the partitioning methodology with golden section has a shorter computing time.

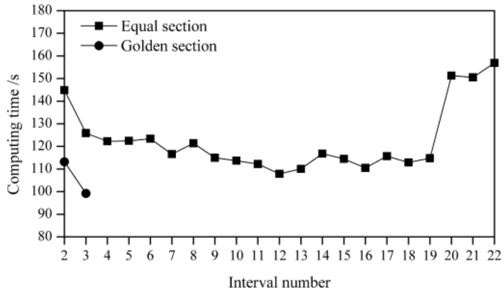

Fig. 2. Computing speed of the algorithms

5. Case Study

A case study [9] will be studied to verify the advance of heat and pressure recovery and the performance of proposed algorithm. The basic data of hydrogen distribution network is shown in Table 3.

Table 3. Hydrogen sources and sinks

Hydrogen flow		Flow rate/g·s^{-1}	Purity	Pressure/MPa	Temperature/°C
Sources	H_2 Plant	1463.1	0.92	2.07	50
	PSA	336.2	0.99	2.07	50
	CCR	687.6	0.75	2.07	300
	HC	282.7	0.75	8.27	300
	DHT	30.1	0.7	2.76	300
	NHT	78.7	0.6	1.38	300
Sinks	HC	1087.0	0.92	13.79	300
	CNHT	186.7	0.89	3.45	200
	DHT	346.4	0.76	4.14	300
	JHT	253.1	0.75	3.45	300
	IS4	1.2	0.75	2.07	300
	NHT	378.3	0.71	2.07	300

The standard chemical exergy of hydrogen is 236.1 kJ·mol^{-1} [10]. Other data are detailedly listed in literature [9]. The calculation will be carried out by GAMS software.

After calculation, the optimal hydrogen distribution network is shown in Fig. 3.

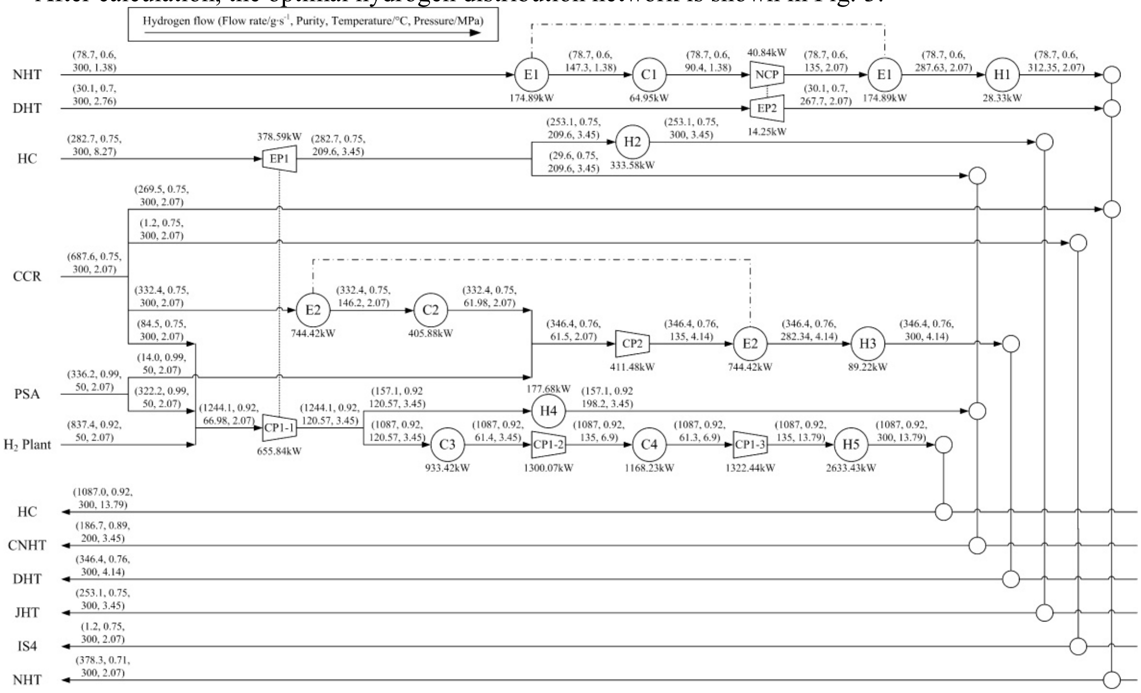

Fig. 3. Optimal hydrogen distribution network

The minimum economic cost per unit exergy of hydrogen sinks is 3.34 $\$\cdot GJ^{-1}$. Hydrogen consumption is 837.4 $g\cdot s^{-1}$, which is the same with literatures [9]. The number of compressors is 5. However, the compressors CP1-1, CP1-2 and CP1-3 could be treated as one compressor with intermediate cooling and discharge. The number of compressors from literature [9] is also 3, which ignored the detailed intermediate cooling process. Other results about energy and economic costs are listed in Table 4.

Table 4. Energy and economic results

Item	Value
Exergy loss in heat exchange process /kW	351.38
Exergy loss in pressure exchange process /kW	373.07
Exergy loss in mixing process /kW	190.66
Total power consumption /MW	3.73
Power recovered by turbines /kW	392.84
Capital cost of compressors /M$	7.47
Capital cost of turbines /k$	677.26
Capital cost of heat exchangers /k$	380.06
Capital cost of pipes /k$	12.16
Annualized operating cost /M$	24.28

The recovery of pressure power could reduce 392.84 kW of power consumption. The reduction of power consumption could save 314.27 $k\$\cdot y^{-1}$, while the capital cost of turbines is 677.26 k$. Therefore, the payback period of turbines is only 2.15 years. The application of turbines could easily cut down energy and economic costs at the same time, which should be popularize in refineries. The heat exchangers recover 919.31 kW heat energy and reduce the energy consumption as well.

6. Conclusions

The optimization of hydrogen distribution network considering pressure and heat recovery is studied in this paper. The optimization problem is solved based on the state space superstructure and exergoeconomic analysis. The algorithm of partitioning methodology is improved by combining with golden section method. A case study from a refinery is studied. The result shows that the consideration of pressure and heat recovery could reduce the energy and economic costs simultaneously. The employment of heat exchangers and rotary work exchangers could reduce the energy consumption greatly. The capital cost of heat exchangers and turbines could easily be paid back by the reduction of operating cost. The exergoeconomic analysis gives out a balanced solution between energy and economic factors, which is a good way for the sustainable development of chemical plants against the background of energy crisis and environment pollution problems. The proposed partitioning methodology with golden section method could solve the problem rapidly and accurately. The consideration of heat and pressure recovery is very necessary for the optimization of hydrogen distribution network in refineries.

Acknowledgements

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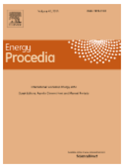

Biography

Professor Zaoxiao Zhang works in the School of Chemical Engineering and Technology, Xi’an Jiaotong University. The research areas are focused on CO_2 capture and sequestration technologies, energy storage and utilization, and new type of chemical machinery.