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Integrating Hydrogen Turbines into Refinery Hydrogen Network for Power Recovery

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The operation pressure levels of refinery hydrogenation units (e.g., hydrocrackers and hydro-treaters) and hydrogen supply units (i.e., hydrogen plant and continuous catalyst reforming unit) are normally different. The hydrogen compressors (i.e., make-up hydrogen and recycle hydrogen compressors) are widely utilized to raise the pressure of the hydrogen-rich streams. The valves are also used to reduce the pressure of hydrogen-rich streams, and this leads to the waste of power. Hydrogen turbines have been successfully applied in practical industrial plants to recover power. This paper presents a novel superstructure of refinery hydrogen networks integrated with hydrogen turbines to recovery the power. The superstructure consists of a hydrogen production plant, a continuous catalyst reforming unit, other hydrogen sources and sinks, hydrogen compressors and turbines. The mathematical model including mass balance and logical constraints is proposed, with the objectives of minimizing flowrate of hydrogen utility and minimizing the difference between consumed power in compressors and recovered power using turbines. A simplified industrial case study is solved to illustrate the proposed methodology. Results show that 1 MW of power can be recovered via the integrated turbines.

1. Introduction

The purchase and processing amount of inferior crude oil has been increasing yearly in modern refineries. At the same time, stricter environmental regulations on sulfide content in the product oil (i.e., the European Standard (EN 228+A1, 2017) and Chinese national standard (GB 17930-2016, 2016)) require that the upper bound of sulfur content in unleaded petrol is 0.001 %. Thus, the proportion of hydrotreating and hydrocracking processes continues to improve, which consume a large amount of hydrogen. Hydrogen effective management has become a critical issue in refineries. On the other hand, compression work which is generated by using compressors to increase pressure raises the operating cost in hydrotreating and hydrocracking processes. It is desirable to conserve energy while optimizing the hydrogen system to save fresh hydrogen in refinery. The methodologies for the optimal synthesis of hydrogen networks include insight-based pinch techniques and mathematical programming approaches.

Alves and Towler (2002) firstly proposed the hydrogen surplus diagram to determine the minimum flowrate of hydrogen utility before detailed hydrogen network design. Then, many other insight-based Pinch techniques have been developed to target the minimum flowrate for hydrogen network, such as the material recovery pinch diagram (El-Halwagi et al., 2003), the source composite curve (Bandyopadhyay, 2006), limiting composite curve (Agrawal and Shenoy, 2006) and the improved problem table (Deng, 2015a). However, these approaches do not consider pressure constraints for hydrogen network. In general, hydro-cracking and hydro-treating processes operate at particular pressure levels. The streams (i.e. make-up hydrogen streams and recycle streams) flowing from low pressure level to higher pressure sinks requires compression work. Ding et al. (2011) proposed the average pressure profiles of hydrogen sources and sinks to determine whether the compressors should be installed or not. Bandyopadhyay et al. (2014) presented a rigorous targeting methodology to minimize compression work in hydrogen allocation network. Their method considered to break hydrogen allocation network with multiple pressure levels into various subproblems having two pressure levels only and minimize

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cross-flows between these pressure levels. In recent years, various mathematical models based on superstructure have been developed to optimize hydrogen network with pressure constraints. Hallale and Liu (2001) proposed a mathematical model based on superstructure which aims to maximize hydrogen recovery in refineries. Their method considers pressure constraints, existing equipment and capital costs. Kumar et al. (2010) developed modified model considering variable inlet and outlet pressures as well as recycle rate of compressor. Jagannath and Almansoori (2017) presented a mathematical programming model for the optimization of hydrogen networks considering minimum compression cost. Deng et al. (2018) presented an improved nearest neighbors' algorithm to design hydrogen networks with minimum compression and it is validated using mathematical models.

It may be noted that no methodology has been presented to recover power when streams flow from higher pressure to lower pressure. In this paper, a novel superstructure of hydrogen network is integrated with hydrogen compressors and turbines. The superstructure consists of hydrogen sources and sinks, hydrogen compressors and turbines and their interconnections. The mathematical formulation mainly includes mass balance equations and logic constraints, with the objective function considering total power consumption. One literature case is analyzed to illustrate the application of proposed approach.

2. Process Description

The problem can be stated as follows. A set of hydrogen sources ($s \in NSR$) can be allocated to hydrogen sinks or discharged to the fuel system. Each hydrogen source has its outlet flowrate (F_{SR_i}), impurity composition (y_{SR_i}) and pressure (P_{SR_i}). A set of hydrogen sinks ($k \in NSK$) accept hydrogen sources via reuse/recycle. Each hydrogen sink is characterized by its required inlet flowrate (F_{SK_j}), upper bound of impurity composition ($y_{SK_j}^{\max}$) and specified pressure (P_{SK_j}). The hydrogen utility is treated as supplementary hydrogen source. Compressors are placed to increase the pressure of hydrogen streams to satisfy the inlet pressure of hydrogen sinks and turbines also can be installed to recover power. It is assumed that the total power consumption of hydrogen network is difference between consumed power in compressors and recovered power by turbines. The aim of this study is designing an optimal hydrogen network with minimum flowrate of hydrogen utility and total power consumption.

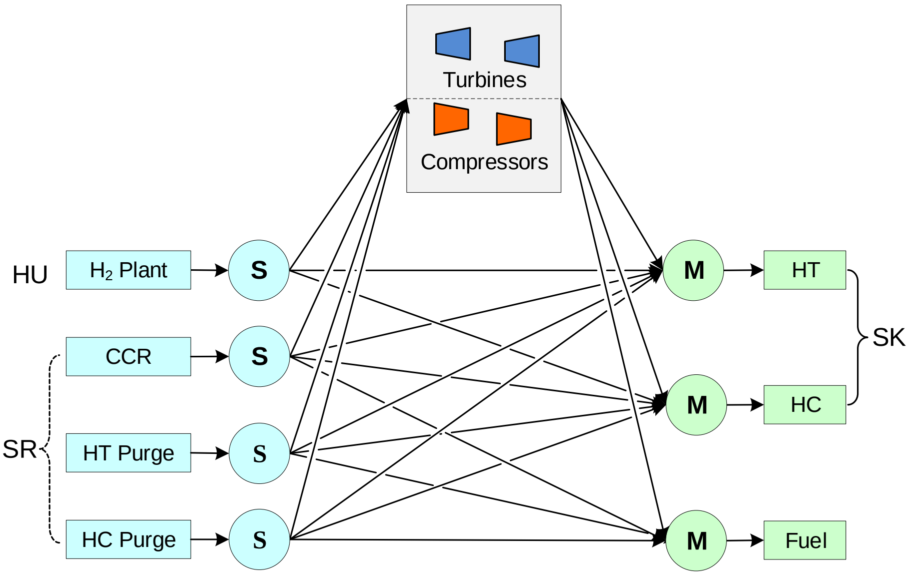

Figure 1: Superstructure of refinery hydrogen network integrated with hydrogen compressors and turbines

3. Mathematical Model

The superstructure of the synthesis of hydrogen network is shown in Figure 1. As shown, HU denotes the hydrogen utility. SR and SK denote the process hydrogen sources and sinks. Fuel system denotes the fuel gas system. S and M denote the splitter and mixer. When the pressure of the hydrogen source is lower than that of the hydrogen sink and the supply relationship exists, the compressor is implied to increase the pressure of hydrogen source. When the pressure of the hydrogen source is higher than that of the hydrogen sink and the supply relationship exists, the turbine is applied to recover power. We present the model formulations for the synthesis of hydrogen network to optimize the flowrate of hydrogen utility and work. A list of indices, sets, parameters and variables are given in the Notation, where all the parameters are denoted with upper-case symbols and all the variables are denoted with lower-case symbols.

3.1 Constraints

The model formulations are extended from our previous work (Deng et.al. 2018). In the previous literature, the formulation of compress work in the objective function is a nonlinear equation, and it is modified to be a linear equation in this paper. Eq.(A14) is the objective function to minimize the compression work. The item $fuk_{u,k} z_{u,k}^{\text{comp}} (\mu_k - \mu_u)$ denotes compression work between U and K, which contains continuous variables and binary variables, resulting in the nonlinearity of the objective function. Compression work $W_{a,b}^{\text{comp}}$ is $fuk_{a,b} \cdot (\mu_b - \mu_a)$ when $z_{a,b}^{\text{comp}}$ is one; compression work $W_{a,b}^{\text{comp}}$ is zero when $z_{a,b}^{\text{comp}}$ is zero. The modified compression work calculation is formulated as Eqs(1-7).

$$W_{a,b}^{comp} \le M_{comp}^{\max} \cdot z_{a,b}^{\text{comp}} \tag{1}$$

$$W_{a,b}^{comp} - fab_{a,b} \cdot (\mu_b - \mu_a) \le (1 - z_{a,b}^{\text{comp}}) \cdot M_{comp}^{\max} \tag{2}$$

$$W_{a,b}^{comp} - fab_{a,b} \cdot (\mu_b - \mu_a) \ge (z_{a,b}^{\text{comp}} - 1) \cdot M_{comp}^{\max} \tag{3}$$

$$W_{a,b}^{comp} \in \left\{ W_{u,k}^{\text{comp}}, W_{s,k}^{\text{comp}} \right\} \tag{4}$$

$$z_{a,b}^{\text{comp}} \in \left\{ z_{u,k}^{\text{comp}}, z_{s,k}^{\text{comp}} \right\} \tag{5}$$

$$fab_{a,b} \in \left\{ fuk_{u,k}, fsk_{s,k} \right\} \tag{6}$$

$$\mu_a \in \left\{ \mu_u, \mu_k, \mu_s \right\} \tag{7}$$

where a and b denote the pressure of the hydrogen supplier and hydrogen receiver. $W_{a,b}^{comp}$ denotes the compression work between hydrogen supplier a and hydrogen receiver b.

When the hydrogen flow rate is not zero and the pressure difference between the hydrogen supplier a and receiver b is positive, turbines can be considered to set to recover power. Eqs(8-9) can be represented as judging the setting of turbines.

$$z_{a,b} = 1 \text{ and } z_{a,b}^{\Delta P} = 0 \rightarrow z_{a,t} = 1 \text{ and } z_{t,b} = 1 \tag{8}$$

$$z_{a,b} \in \left\{ zuk_{u,\text{k}}, zsk_{s,\text{k}} \right\} \tag{9}$$

The logical constraint (i.e. Equation (8)) is formulated as Eq.(10):

$$-z_{a,b} + z_{a,b}^{\Delta P} + z_{a,b}^{\text{turbine}} \ge 0 \tag{10}$$

$$z_{a,b}^{\text{turbine}} \in \left\{ z_{u,k}^{\text{turbine}}, z_{s,k}^{\text{turbine}}, z_{s,f}^{\text{turbine}} \right\} \tag{11}$$

where $z_{a,b}^{\text{turbine}}$ is binary variable. When $z_{a,b}$ is one and $z_{a,b}^{\Delta P}$ is zero, the value of $z_{a,b}^{\text{turbine}}$ must be one, or else the value of $z_{a,b}^{\text{turbine}}$ can be one or zero.

When $z_{a,b}^{\text{turbine}}$ is one, the work $W_{a,b}^{\text{turbine}}$ recovered by turbine is $fuk_{a,b} \cdot (\mu_a - \mu_b)$; if $z_{a,b}^{\text{turbine}}$ is zero, the work $W_{a,b}^{\text{turbine}}$ is zero also. The logical calculations can be expressed by Eqs(12-18).

$$W_{a,b}^{turbine} \le M_{turbine}^{\max} \cdot z_{a,b}^{\text{turbine}} \tag{12}$$

$$W_{a,b}^{turbine} - fab_{a,b} \cdot (\mu_a - \mu_b) \le (1 - z_{a,b}^{turbine}) \cdot M_{turbine}^{\max} \tag{13}$$

$$W_{a,b}^{turbine} - fab_{a,b} \cdot (\mu_a - \mu_b) \geq (z_{a,b}^{turbine} - 1) \cdot M_{turbine}^{\max} \tag{14}$$

$$W_{a,b}^{turbine} \in \left\{ W_{u,k}^{turbine}, W_{s,k}^{turbine}, W_{s,f}^{turbine} \right\} \tag{15}$$

$$z_{a,b}^{turbine} \in \left\{ z_{u,k}^{turbine}, z_{s,k}^{turbine}, z_{s,f}^{turbine} \right\} \tag{16}$$

$$fab_{a,b} \in \left\{ fuk_{u,k}, fsk_{s,k}, fsf_{s,f} \right\} \tag{17}$$

$$\mu_a \in \left\{ \mu_u, \mu_k, \mu_s, \mu_f \right\} \tag{18}$$

where $W_{a,b}^{turbine}$ denotes the work recovered by the hydrogen supplier a and hydrogen receiver b.

3.2 Objective functions

The flow rate of hydrogen utility can be minimized to reduce the capacity of hydrogen plant and its operating cost. The objective function is given by Eq(A13) in Appendix A Mathematical Model of literature (Deng et al., 2018).
The energy takes great part of operating cost of hydrogen network and the objective function is reformulated to solve the minimum total power consumption, which can be formulated as Eq(19).

$$\begin{aligned} \min \ W_{total} = & \sum_{u \in NHU} \sum_{k \in NSK} W_{u,k}^{comp} + \sum_{s \in NSR} \sum_{k \in NSK} W_{s,k}^{comp} \\ & - \sum_{u \in NHU} \sum_{k \in NSK} W_{u,k}^{turbine} - \sum_{s \in NSR} \sum_{k \in NSK} W_{s,k}^{turbine} - \sum_{s \in NSR} \sum_{f \in NSF} W_{s,f}^{turbine} \end{aligned} \tag{19}$$

3.3 Model summary

Two models (P1 and P2) are considered in sequence for the synthesis of hydrogen network with minimum total work.
P1 – minimum flowrate of hydrogen utility fhu as objective function (Deng et al., 2018),
P2 – minimum   as objective function
min   given in Eq(19)
s.t. mass balance constraints (A1)(A2)(A3)(A4) and (A6)
composition constraint (A5)
pressure index calculation $\mu = P_0 \ln\left(\frac{P}{P_0}\right)$ for isothermal process and $\mu = \left(\frac{\gamma}{\gamma - 1}\right) P_0 \left(\frac{P}{P_0}\right)^{\frac{\gamma - 1}{\gamma}}$ for adiabatic/polytrophic process;
logic constraints: (A7)(A9)(A10) and Eqs(10-11)
connection constraints: (A11)
number of compressors: (A12)
compression work: Eq(1-7)
turbine work: Eqs(12-18)
All the models are coded in GAMS 24.2.1 on a PC with an Intel(R) Core^{TM} i7-4790 CPU 3.60 GHz, 8 GB RAM, running Window 7, 64-bit operating system. The LP and MILP problems are solved using CPLEX. The absolute optimality tolerance for all solvers is set as 10^{-6}.

4. Case Study

The Limiting data shown in Table 1 for the refinery hydrogen network is extracted from the literature (Hallale and Liu, 2001). The outlet hydrogen streams of naphtha hydro-treating (NHT), jet fuel hydrotreating (JHT), cracked naphtha hydrotreater (CNHT), diesel hydrotreater (DHT), hydrocracker (HC) and catalytic reformer (CCR) are taken as process hydrogen sources (denoted as S1, S2, S3, S4, S5, S6, respectively). The inlets of NHT, JHT, CNHT, DHT, HC and isomerization (IS4) are considered as process hydrogen sinks (denoted as D1, D2, D3, D4, D5, D6, respectively). The hydrogen utility (denoted as S0) is supplied via hydrogen production plant. The surplus hydrogen source discharged to the fuel system is denoted as D0.

Table 1: Limiting data for hydrogen network

Type		Impurity composition (mole fraction)	Flow rate ($Sm^3 \cdot s^{-1}$)	Pressure (kPa)	$\mu_{adiabatic}$ ($kJ \cdot Sm^{-3}$)
Sources	H_2 plant (S0)	0.08	**14.598**	2,068	839.55
	NHT (S1)	0.4	3.324	1,379	747.72
	JHT (S2)	0.35	2.596	2,413	877.36
	CNHT (S3)	0.25	13.183	2,413	877.36
	DHT (S4)	0.3	3.334	2,758	911.48
	HC (S5)	0.25	31.791	8,274	1,247.55
	CCR (S6)	0.25	3.359	2,068	839.55
Sinks	NHT (D1)	0.312	5.136	2,068	839.55
	JHT (D2)	0.279	4.015	3,447	971.48
	CNHT (D3)	0.229	14.737	3,447	971.48
	DHT (D4)	0.248	4.219	4,137	1,023.43
	HC (D5)	0.197	40.802	13,790	1,443.61
	IS4 (D6)	0.25	0.013	2,068	839.55
	Fuel system (D0)	0.4	**3.263**	1,379	747.72

The minimum flowrate of hydrogen utility supplied by hydrogen production plant and the flowrate of waste hydrogen to be discharged to the fuel system are determined to be 14.598 $Sm^3 \cdot s^{-1}$ and 3.263 $Sm^3 \cdot s^{-1}$ via solving mathematical model P1.

For the results comparison with our previous work (Deng et al., 2018), the upper bound of the connections is set to 17, and the upper bound of compression work is set to 15.09 MW. Solving the mathematical model P2, the minimum total power consumption of the hydrogen network is 14.09 MW. The total compression power is still identical with 15.09 MW, while the recovered power via turbines is 1 MW. Thus, the result reduced by 1 MW compared with that reported in our previous work (Deng et al., 2018) and the literature (Bandyopadhyay et al., 2014).

Based on optimization results of mathematical model P2, the optimal hydrogen network can be plotted shown as Figure 2.

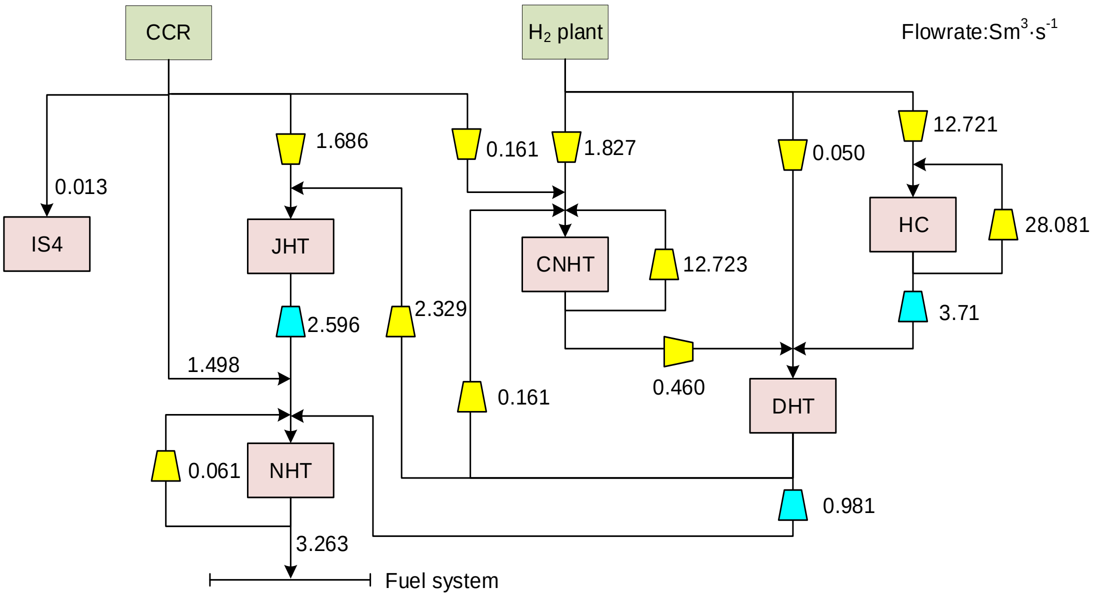

Figure 2: One optimum hydrogen network and the placement of compressors and turbines

5. Conclusions

In this paper, a novel superstructure of refinery hydrogen networks integrated with hydrogen turbines is proposed. Two sequential mathematical models (i.e. P1 and P2) are proposed to determine the minimum flowrate of hydrogen utility and total power consumption. One literature case is analyzed to show the applicability and feasibility of the proposed model. Results show that 1 MW of power can be recovered via the placement of hydrogen turbines. Future work will consider the hydrogen network with purification reuse/recycle, the cost of equipment and the optimization of operating costs.

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