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Flowrate Targeting for Interplant Hydrogen Networks

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In this paper, the improved problem table (IPT) is referred to locate the flowrate targets of interplant hydrogen conservation network. Firstly, the flowrate targets for individual hydrogen networks are located and the purge gas streams can be identified via IPT. Next, the IPT is utilized to determine the flowrate targets for the overall interplant hydrogen network. The arising problems with multiple resources and purge gas streams can be coped with by IPT. One example is solved to show the effectiveness and applicability of the proposed approach. The results show that the flowrate of hydrogen utility (0.01) for Plant B is reduced by 1,784 Nm^3/h and the hydrogen utility (0.05) for Plant A is totally conserved.

1. Introduction

The processing ratio of high-sulfur, heavy and poor-quality crude oil has been increasing yearly, i.e. Sinopec imported high sulphur crude oil is up to 70 Mt in 2010 and the year-on-year growth reached 17 %. On the other hand, tighter environmental regulations and policies on sulphide and aromatics content are leading to higher oil products quality requirements for refineries. In order to improve the oil products quality, refineries has to increase the depth of hydrotreating and hydrocracking processes, which consume large amount of fresh hydrogen. On the other hand, the operation capacity of traditional continuous catalyst reforming, an important hydrogen producing process, is reduced because of the shrinking market demand for reforming products. Therefore, the gap between these consuming and producing processes aggravates the fresh hydrogen shortage in refineries, making fresh hydrogen a more and more expensive resource for modern refineries. It is quite necessary to enhance the hydrogen network management in the inner refinery plant. However, the recovered hydrogen is sometimes far insufficient to satisfy the sharp increasing demand. Instead of introducing hydrogen production process to produce fresh hydrogen, it is an attractive alternative to recover the hydrogen from other plants (i.e. fertilizer, ethylene plants) in the petrochemical industrial park. Hence, there is a necessity to address the synthesis of interplant hydrogen system.

Generally, the methodologies in previous work on the synthesis and retrofit of refinery hydrogen network can be classified into two aspects: pinch technique, such as, hydrogen surplus diagram (Alves and Towler, 2002), gas cascade analysis (Foo and Manan, 2006), improved limiting composite curve (Agrawal and Shenoy, 2006) and mathematical programming approaches, such as first superstructure model with pressure constraint (Hallale and Liu, 2001), systematic methodology for the selection of appropriate purifiers (Liu and Zhang, 2004), state-space superstructure (Liao et al., 2010), multi-component and integrated flash calculation (Jia and Zhang, 2011), hydrogen sulphide removal process embedded optimisation model (Zhou et al., 2012), total exergy consumption of the hydrogen utility and compressor work (Wu et al., 2012), strategy for hydrogen integration in petroleum refining (Smith et al., 2012), and key factor analysis for hydrogen integration (Deng et al., 2013). However, few researches have been reported on the synthesis of interplant hydrogen network in the literature. Gas cascade analysis is utilized to locate the interplant hydrogen conservation network with unassisted integration scheme (Chew et al., 2010) and assisted integration scheme (Chew et al., 2010). In the flowrate targeting for interplant hydrogen networks, the arising problems, such as network with multiple-resources and purge gas stream identification, are coped with via their former proposed techniques, water cascade analysis (Foo, 2007) and waste stream identification(Ng et al., 2007).

In this paper, the Improved Problem Table - IPT (Deng and Feng, 2011) is explored to target the flowrate of interplant hydrogen network. Flowrate targets for individual hydrogen networks are determined and the purge gas streams for each hydrogen network can be identified via IPT firstly. Next, the improved problem table is employed to determine the flowrate targets for the overall interplant hydrogen network. One literature example is analysed to illustrate the applicability of the proposed approach.

2. Problem statement

The problem can be stated as follows. Given several refinery or chemical plants, there is a set of hydrogen-consuming utilities in each plant, their outlet streams are treated as a set of internal hydrogen sources ($i \in NSR$) while inlet streams treated as a set of hydrogen sinks ($j \in NSK$). Each hydrogen source is specified by its outlet flow rate (F_{SRi}) and outlet hydrogen purity (y_{SRi}). Each hydrogen sink has inlet flow rate (F_{SKj}) and lower limit of inlet hydrogen purity ($y_{SKj}^{\lim}$). Hydrogen sources can be reused/recycled to fulfil the requirements of hydrogen sinks. Besides, a set of external hydrogen sources or hydrogen utilities ($u \in NHU$) are needed for supplement. To reduce the common dosage of hydrogen, the internal hydrogen sources would be recycle/reused as much as possible. And the surplus hydrogen sources are discharged to fuel system. For the interplant integration scheme of three refinery or chemical plants, the surplus hydrogen sources discharged from Plant A can be allocated to Plant B, and high purity of hydrogen from Plant B would be allocated to Plant C, and surplus hydrogen sources would be distributed from Plant C to Plant A. This paper aims to target the minimum hydrogen utility flow rates for interplant hydrogen networks.

3. Flowrate targeting for interplant hydrogen networks by IPT

In this section, IPT is referred to locate the minimum flow rates of hydrogen utilities for individual plants and interplants (two and three plants).The limiting data shown in Table 1 for three plants are extracted, Plant A (Alves and Towler, 2002), Plant B (Hallale and Liu, 2001) and Plant C (Foo and Manan, 2006). Note that all the flowrate units are unified to be Nm^3/h.

3.1 Flowrate targeting for individual hydrogen networks

The minimum flow rates of hydrogen utilities for individual plants (i.e. Plant A) are targeted by IPT and the detailed steps for IPT can be referred to the literature (Deng and Feng, 2011).

Step 1: Tabulate all purities of hydrogen sources and sinks (data for Plant A shown in Table 1) in decreasing order in the first column (Table 2). Do not repeat the same purity that occurs more than once. Add one more arbitrary purity at the bottom of the column so that it is the smallest value. The arbitrary purity serves to provide an end point and facilitates the plotting of the last segment of the limiting composite curve. The second column shows impurities that is 1- *y*.

Step 2: Tabulate the net flow rates in the third column (Table 2) by subtracting the sum of the flow rates of the hydrogen sources from the sum of the flow rates of hydrogen sinks in each purity interval. Besides, the net flow rate corresponds to the reciprocal of the slope of a segment on the limiting composite curve. And the last value in the third column (Table 2) which is obtained by subtracting the sum of all flow rates of the hydrogen sources from the sum of all flow rates of the hydrogen sinks determines the minimum net flow rate of external hydrogen sources for the network. For a given hydrogen network, the value is a constant. For Plant A, the minimum net flow rate for external hydrogen sources is 13,410 Nm^3/h.

Step 3: Tabulate the net mass loads in the fourth column (Table 2). The net mass loads for each purity internal are the products of the net flow rates and the purity differences of the corresponding intervals.

Step 4: Tabulate the cumulative mass loads in the fifth column (Table 2). The first row has no cumulative mass load so that it equals zero. The cumulative mass loads of other rows are accumulated by the net mass loads above the row. The impurity column can be plotted against the cumulative mass load column to obtain the limiting composite curve and it is omitted for simplification.

Step 5: Tabulate the possible hydrogen supply flow rates for each purity (FHU_u^v) in the sixth column using Eq(1).

$$F_{HUu}^{v} = \frac{\Delta M_{cum}^{v}}{y_{HUu} - y^{v}} \quad (1)$$

Table 1: Limiting hydrogen data

Hydrogen Network	Hydrogen Sources	Purity (fraction)	Flow rate (Nm^3/h)	Hydrogen Sinks	Purity (fraction)	Flow rate (Nm^3/h)
A	SRU	0.93	50,303	HCU	0.8061	201,197
	CRU	0.8	33,530	NHT	0.7885	14,531
	HCU	0.75	145,305	DHT	0.7757	44,707
	NHT	0.75	11,177	CNHT	0.7514	58,117
	DHT	0.73	27,942			
	CNHT	0.7	36,885			
	Fresh supply A	0.95	22,353 (current)			
B	S1	0.91	390,705	D1	0.928	446,520
	S2	0.85	558,150	D2	0.8757	669,780
	Fresh supply B	0.99	223,260 (current)			
C	SR1	0.983	6,451	SK1	0.999	9,677
	SR2	0.85	6,048	SK2	0.986	2,242
	SR3	0.96	2,302	SK3	0.975	6,451
	SR4	0.95	6,451	SK4	0.975	4,838
	SR5	0.9	9,677	SK5	0.97	9,677
	SR6	0.983	3,226	SK6	0.9	12,096
	SR7	0.975	6,451			
	Fresh supply C	0.999				

Table 2: Implementation of IPT for Plant A

Purity (fraction)	Impurity (fraction)	Net flow rate (Nm^3/h)	Net load (Nm^3/h)	Cumulative load (Nm^3/h)	Fresh supply A (Nm^3/h)	Flow rate above Pinch (Nm^3/h)	Flow rate for Purge gas stream (Nm^3/h)
0.95	0.05						
0.93	0.07						
0.8061	0.1939	-50,303	-6,233	-6,233	-43,312		
0.8	0.2	150,894	920	-5,312	-35,414		
0.7885	0.2115	117,363	1,350	-3,962	-24,535		
0.7757	0.2243	131,895	1,688	-2,274	-13,048		
0.7514	0.2486	176,602	4,291	2,017	10,157		
0.75	0.25	234,719	329	2,346	11,729		
0.73	0.27	78,237	1,565	3,911	17,775		
0.7	**0.3**	50,295	1,509	5,419	**21,678**		8,267
0.65	0.35	13,410	671	6,090	20,300	13,410	

where ΔM^{v}_{cum} and y^{v} denotes the cumulative mass load and purity concentration for *v*th purity level and y_{HUu} denotes the purity of *u*th external hydrogen source.

The maximum value in sixth column of Table 2 is 21,678 Nm^3/h (=268.82 mol/s) and it is marked in bold. It is bigger than the minimum net flow rate (13,410 Nm^3/h) determined in Step 2 and the maximum value (21,678 Nm^3/h) is considered to be the minimum flow rate of fresh hydrogen, and the corresponding impurity concentration (0.3) is identified as the pinch impurity concentration. The result is agree with that reported in the literature(Alves and Towler, 2002). Negative values in the sixth column indicate that internal hydrogen sources can meet the demand of hydrogen sinks without the supply of external fresh hydrogen sources. Besides, if the maximum value in the sixth column is smaller than the minimum net flow rate determined in Step 2, the minimum net flow rate is considered as the the minimum flow rate of fresh hydrogen for the network.

Step 6 (Only for the network with multiple external hydrogen sources)**:** Tabulate all possible flow rates of other external hydrogen sources in the following columns.

Step 7: Identify purge gas streams discharged from the network. On the pinch (the impurity concentration is 0.3), the accumulated hydrogen flow rate is 21,678 Nm^3/h. It can be considered as an internal hydrogen source with the impurity of 0.3. Then for each impurity interval above 0.3, the required flowrates can be calculated via Eq.(2) and all possible flow rates for F_P are listed in the seventh column of Table 2 and the maximum value (13,410 Nm^3/h) determines the target. Therefore, only 13,410 Nm^3/h of hydrogen source at the impurity of 0.3 needs to be distributed to the system and the residual flow rate 8,268 Nm^3/h (=21,678 Nm^3/h –13,410 Nm^3/h) is identified as the purge gas stream WH1 (0.3).

$$F_{pinch} = \frac{\Delta M_{cum}^{v} - \Delta M_{cum}^{pinch}}{y_{pinch} - y^{v}} \quad \forall y^{arbitrary} \le y^{v} < y_{pinch} \tag{2}$$

Step 8: Use nearest neighbours algorithm (NNA)(Prakash and Shenoy, 2005) to design the hydrogen network. The hydrogen network for Plant A consumes 21,678 Nm^3/h of hydrogen utility (0.05) and discharge 8,267 Nm^3/h of purge gas stream (0.3), which are identical to those calculated by IPT.

Similarly, IPT is used to target the hydrogen network for Plants B and C. For Plant B, the minimum hydrogen utility (impurity of 0.01) is located as 204,125 Nm^3/h with pinch impurity concentration (0.15) and the purge gas stream is identified as 36,680 Nm^3/h (0.15). For Plant C, the minimum hydrogen utility (impurity of 0.001) is located as 10,097 Nm^3/h with pinch impurity concentrations (0.017 and 0.05) and the purge gas streams are identified as 2,497 Nm^3/h (0.05) and 4,838 Nm^3/h (0.15).

3.2 Flowrate targeting for interplant hydrogen networks

Firstly, the interplant integration between two plants is explored. For Plants A-B, the purge gas stream from Plant B is identified as 36,680 Nm^3/h (0.15). The impurity concentration (0.15) of purge gas stream of Plant B is lower than the pinch impurity concentration for Plant A (0.3). Therefore, the purge gas stream of Plant B can be allocated to Plant A and the minimum flowrate for purge gas stream of Plant B is located as 36,130 Nm^3/h. The purge gas stream of Plant B is sufficient and the fresh supply A is totally conserved. The flow rates for hydrogen utilities can be further reduced from 21,678 Nm^3/h (0.05) + 204,125 Nm^3/h (0.01) to 204,125 Nm^3/h (0.01). The interplant hydrogen network for Plants A-B can be synthesized by NNA (Prakash and Shenoy, 2005). Similarly, the interplant integration for Plants B-C and Plants A-C are investigated and the IPTs and interplant hydrogen networks are omitted for brevity.

Next, the interplant integration among three plants is investigated. The purge gas streams from Plants B-C are identified as 4,838 Nm^3/h (0.15) (Plant C) + 37,393 Nm^3/h (0.15) (Plant B). The impurity concentrations for the purge gas streams are less than the pinch impurity (0.3) of Plant A. Therefore, the purge gas streams of Plants B-C can be allocated to Plant A and the minimum flowrate for purge gas stream of Plants B-C is located as 36,130 Nm^3/h. The interplant hydrogen network for Plants A-B-C as shown in Figure 1 can be synthesized by NNA (Prakash and Shenoy, 2005) and it is marked as Scenario 1. The flow rates for hydrogen utilities are targeted as 10,097 Nm^3/h (0.001, Plant C) + 202,341 Nm^3/h (0.01, Plant B). The purge gas streams are identified as 6,101 Nm^3/h (0.15, Plant B) + 22,710 Nm^3/h (0.3, Plant A).

In addition, the purge gas stream from Plants C-A is identified as 10,203 Nm^3/h (0.3) and there are two hydrogen streams from Plant C to Plant A. And the purge gas stream from Plant B is identified as 36, 680 Nm^3/h (0.15), which is less than the pinch impurity concentration (0.3) of Plant A. Therefore the purge gas stream of Plant B can be allocated to Plant A and the minimum flowrate for purge gas stream of Plant B is located as 27,130 Nm^3/h. The interplant hydrogen network for Plants A-B-C as shown in Figure 2 can be synthesized by NNA(Prakash and Shenoy, 2005) and it is marked as Scenario 2. The flow rates for hydrogen utilities are targeted as 10,097 Nm^3/h (0.001, Plant C) + 204,125 Nm^3/h (0.01, Plant B). The purge gas streams are identified as 9,550 Nm^3/h (0.15, Plant B) + 21,055 Nm^3/h (0.3, Plant A).

Besides, the interplants B-A would be integrated with Plant C. The purge gas streams of Plant C would allocated to Plant B or Plant A. If the purge gas streams of Plant C is distributed to Plant B, the results and interplant network are identical to those in Scenario 1. Otherwise, the results and interplant network are identical to those in Scenario 2.

Compare the results of Scenario 1 with those of Scenario 2, in Scenario 1, cross-plant gas streams are 2,497 Nm^3/h (0.05, from Plant C to Plant B), 4,838 Nm^3/h (0.15, from Plant C to Plant A) and 31,292 Nm^3/h (0.15, from Plant B to Plant A). In Scenario 2, cross-plant gas streams are 2,497 Nm^3/h (0.05) and 4,838 Nm^3/h (0.15) (from Plant C to Plant A), and 27,130 Nm^3/h (0.15, from Plant B to Plant A). Due to the different direction of 2,497 Nm^3/h (0.05) of cross-plant gas stream (from Plant C to Plant B in Scenario 1 while from Plant C to Plant A in Scenario 2), Plant B consumes 1,784 Nm^3/h of hydrogen utility in Scenario 1 less than that in Scenario 2. It means that Scenario 1 is better than Scenario 2.

In addition, compared with the flowrate targets for individual hydrogen network, the flowrate targets for overall hydrogen network is reduced from 10,097 Nm^3/h (0.001, Plant C) + 204,125 Nm^3/h (0.01, Plant B) + 21,678 Nm^3/h (0.05, Plant A) to 10,097 Nm^3/h (0.001, Plant C) + 202,341 Nm^3/h (0.01, Plant B). For

Plant B, the flowrate of hydrogen utility (0.01) is reduced by 1,784 Nm^3/h. Besides, the hydrogen utility (0.05) for Plant A is totally conserved.

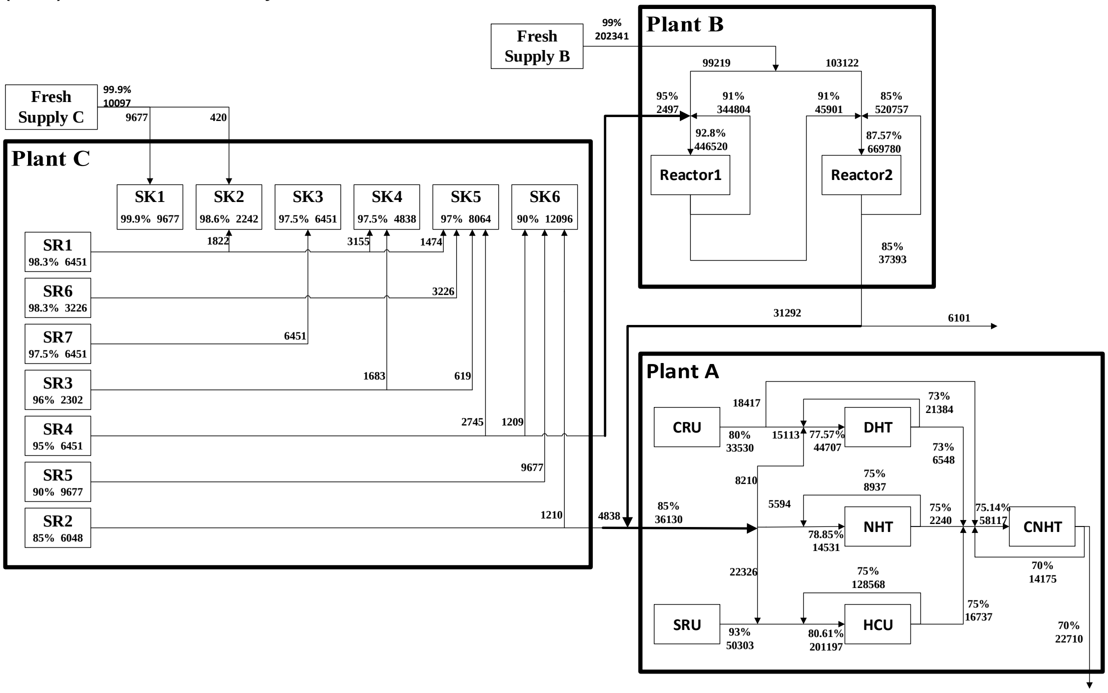

Figure 1: Interplant hydrogen network for A-B-C (Scenario 1)

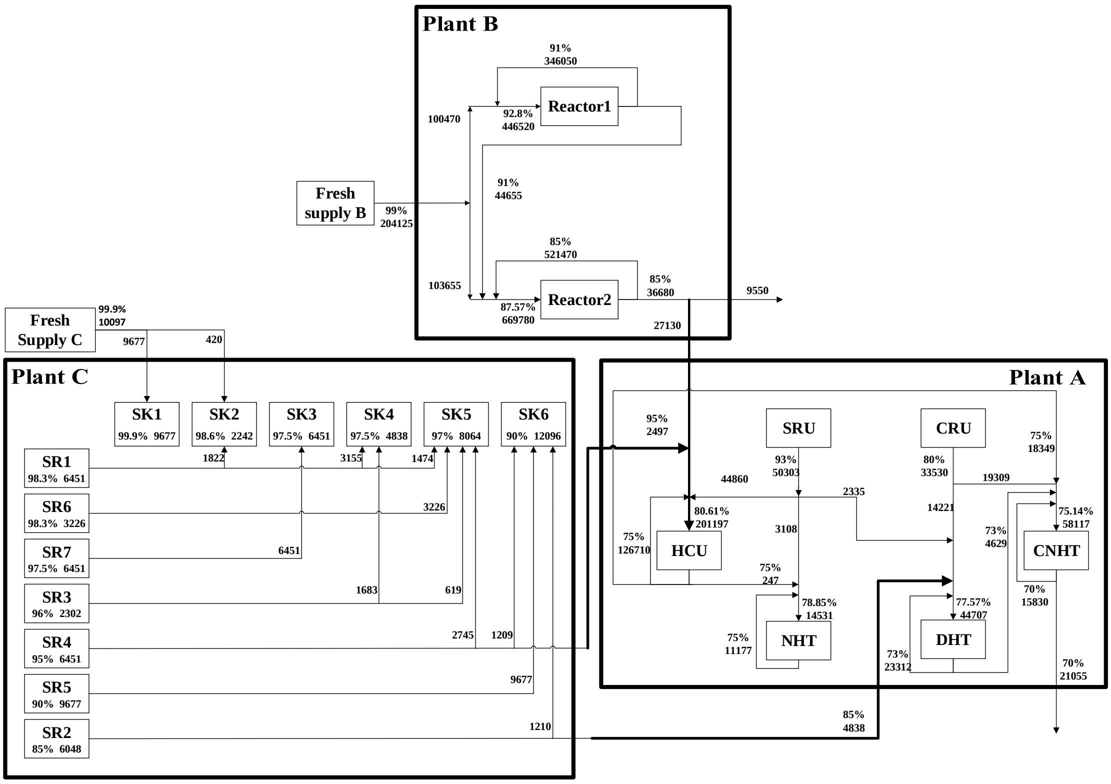

Figure 2: Interplant hydrogen network for A-B-C (Scenario 2)

4. Conclusions

In this paper, the flowrate targets for interplant hydrogen conservation networks are located via the former proposed improved problem table (IPT). Firstly, the flowrate targets for individual hydrogen networks are determined and the purge gas streams are identified via IPT. Next, the improved problem table is utilized to locate the flowrate targets for the overall interplant hydrogen network. The network with multiple resources and purge gas streams can be deal with by IPT. The example with three plants illustrates the effectiveness and applicability of the proposed approach. The results show that the flowrate of hydrogen utility (0.01) for Plant B is reduced by 1,784 Nm^3/h and the hydrogen utility (0.05) for Plant A is totally conserved.

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