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Systematic approach for targeting interplant hydrogen networks

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ABSTRACT

This study proposes a systematic method for targeting the interplant hydrogen network with direct and purification reuse/recycle schemes. The generalized Improved Problem Table is proposed to locate the flowrate targets of individual and interplant hydrogen networks. The constructed limiting composite curves and optimal hydrogen supply lines are utilized to illustrate the insights of the proposed approach. The generalized Improved Problem Table incorporated with mass balance equations is applied to determine the optimal targets (i.e. the optimal flowrates of hydrogen utility and product of the purifier, optimal feed impurity of purifier) of hydrogen network with purification reuse/recycle. Two scenarios of interplant hydrogen integration with direct reuse/recycle are investigated. The case study shows that the conservation ratio of the flowrate of hydrogen utility in Scenario 2 is greater than or equal to that in Scenario 1 and that with purification reuse/recycle scheme is increased sharply. Meanwhile the optimal feed impurity of purifier is greater than or equal to the pinch impurity with direct reuse/recycle scheme. The energy performance evaluation shows that interplant hydrogen integration offers an impressive way to reduce the equivalent energy consumption.

1. Introduction

The processing amount of inferior crude oil has been increasing yearly all over the world. For example, Sinopec, one of the main Chinese refinery companies, imported high sulfur crude oil up to 70 million ton in 2010 and the annual growth rate is around 17%. The environmental regulations and policies on sulfide and aromatics contained in product oil became tighter recently. Both the European Standard (CSN EN 228-2008) and Chinese standard (GB 17930-2013) specify unleaded petrol with a maximum sulfur content of 0.001%. Refineries have been increasing the processing ratio of hydrotreating and hydrocracking processes, which consume a large amount of hydrogen. The operation capacity of the traditional continuous catalyst reforming, an important hydrogen producing process, is reduced because of the shrinking market demand for reforming products. The hydrogen deficit 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. Hydrogen production technologies, such as steam reforming of natural gas or methane are commonly utilized to produce hydrogen to supplement the deficit. However, the hydrogen production is the typical high energy consumption process. For instance, the actual monthly equivalent energy consumption in early 2012 was 4.074×10^7 kJ per ton of produced hydrogen with the purity of 99.9% in Yanshan petrochemical hydrogen plant [1]. The equivalent energy consumption consists of fuel gas, power, desalted water, 1.0 MPa steam and cooling water. The generated 3.5 MPa steam as the negative energy consumption can be sent to steam system. Most recently, the equivalent energy consumption for imported pure hydrogen for a refinery is specified as 4.6055×10^7 kJ per ton in the Chinese standard for comment (GB/T 50441-2015). Other new alternative techniques for hydrogen production are investigated, such as renewable hydrogen production unit through water electrolysis with solar power [2], energy–exergy-based assessment and parametric study of a hydrogen production process using steam glycerol reforming [3], thermodynamic evaluation of geothermal energy powered hydrogen production by water electrolysis [4], hybrid feedstocks (i.e. switchgrass and shale gas) for the simultaneous production of hydrogen and liquid fuels [5]. Hydrogen integration has been an effective tool to recover hydrogen and reduce the capacity of hydrogen plant. However, the recovered hydrogen in

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single plant is sometimes far insufficient to satisfy the sharp increasing demand. An attractive alternative way is to recover the hydrogen from other plants (i.e. fertilizer, ethylene plants, other refineries) in the petrochemical industrial park. For instance, the hydrogen recovery from ethylene plant with composite membrane is investigated [6]. Hence, there is a necessity to explore the possibility of interplant hydrogen integration.

1.1. In-plant hydrogen integration

The methodologies on the synthesis of refinery hydrogen network can be categorized into two types: insight-based pinch technique and superstructure-based mathematical programming approach. Alves and Towler [7] firstly introduced the Hydrogen Surplus Diagram (HSD) to identify the pinch and locate the minimum flowrate of hydrogen utility prior to detailed network design. Many other insight-based pinch techniques, such as Material Recovery Pinch Diagram (MRPD) [8], Source Composite Curve (SCC) [9], Gas Cascade Analysis (GCA) [10], Material Surplus Composite Curve (MSCC) [11], Composite Algorithm Table (CAT) [12] and extended Limiting Composite Curve (LCC) [12], have been developed to determine the flowrate targets for hydrogen networks.

After the maximum hydrogen recovery via direct reuse/recycle, the purifiers (i.e. Pressure swing absorption (PSA), membrane, cryogenic) can be incorporated into the hydrogen network to upgrade the process hydrogen sources and the purified hydrogen stream can be re-utilized by certain hydrogen sinks to reduce the flowrate of hydrogen utility. The option is widely applied in current refinery plant. Hallale [13] investigated the options for the placement of purifier and pointed out that there are three possible placements for the purifier: above the pinch, below the pinch and across the pinch, and found the best option is to place the purifier across the pinch. Foo et al. [10] determined the flowrate targets for the hydrogen network with purification reuse via GCA. The pinched process hydrogen source is divided into two parts: one part is allocated to above the pinch region and the other is sent to below the pinch region. Agrawal and Shenoy [12] located the optimal flowrate targets via CTA and the pinch concentration is assumed to be the optimal purification concentration. Zhang et al. [14] extended the MRPD [8] with the integrated polygon rule to determine the minimum utility consumption of the hydrogen system with purification reuse. Later, Yang et al. [15] simplified and improved the previous approach [14] to identify the maximum hydrogen savings potential with the constraints of concentration and flowrate on purifiers. It is improved later to determine the minimum feed flowrate and minimum tail gas flowrate for the purifier with the maximized savings on hydrogen utility [16]. Recently, Zhang et al. [17] extend the previous approach [14] to optimize both purity and flowrate of the feed and output streams of the purifier within the corresponding feasible operating ranges of purifiers and network feasibility. According to the characteristics of the pinch point, Liu et al. [18] developed a graphical method on the basis of HSD [7] to identify the upper bound of the purification feed flowrates. This technique was then extended to determine the optimal purification feed flowrates for hydrogen networks with purification reuse/recycle [19]. However, only one internal hydrogen source is fed into the purification unit [19] and the targeted flowrate of hydrogen utility cannot be guaranteed as the minimum value. In addition, the optimal conditions for locating the targets for hydrogen networks without [20] and with one purification process [21] are deduced and a rigorous systematic targeting approach based on mathematical deduction is developed. A hydrogen network fulfilling the flowrate targets can be obtained using the Nearest Neighbors Algorithm (NNA) [22] and the preliminary hydrogen network can be evolved with the evolution strategies [23]. An evolutionary method [24] was proposed for the design of resource allocation networks with multiple impurities.

Superstructure-based mathematical programming is also a useful tool for the synthesis of hydrogen network. Hallale et al. [25] firstly proposed a superstructure embedded with hydrogen sources, sinks and compressors, and then optimized it mathematically to maximize hydrogen recovery in the clean fuels production process. Many other mathematical programming approaches were developed. These include the automated targeting technique for direct reuse/recycle [26] and purification reuse [27], overall refinery optimization [28], systematic methodology for selecting appropriate purifiers [29], multi-period optimization models [30], optimization under uncertainty on chance constrained programming [31] and on robust optimization model [32] and multiple operating scenarios [33], state-space superstructure [34], superstructure-based formulation integrated with flash calculation [35], hydrogen sulfide removal [36], unit models for fuel cells and steam reforming plants [37], total CO_2 emission evaluation [38], minimizing the total exergy consumption of the hydrogen utility and compressor work [39], comparative analysis of different scenarios [40], superstructure with intermediate hydrogen header [41], integrated with simplified models for hydroprocessors [42].

1.2. Interplant hydrogen integration

The previous reviewed literature can be categorized into the area of in-plant hydrogen integration. However, many works have been conducted on the synthesis of interplant heat exchange networks, i.e. targeting and design methodology for reduction of fuel, power and CO_2 on total sites [43], targeting for energy savings by heat integration across plants [44], total site heat integration across many plants [45], multiple plant heat integration in a total site [46], industrial application issues of total site heat integration [47], and water networks, such as, design of flexible multiple plant water networks [48], direct and indirect interplant water network [49], plant-wide integration for water network synthesis [50], automated targeting for interplant water integration [51], design of interplant water network with central and decentralized water mains [52], global optimization in property-based interplant water integration [53]. Few researches have been conducted on the synthesis of interplant hydrogen network. GCA is utilized to locate the interplant hydrogen conservation network with unassisted integration scheme [54] and assisted integration scheme [55]. In the flowrate targeting for interplant hydrogen networks, the arising problems, such as network with multiple-resources and waste hydrogen stream identification, are coped via the procedure for the network targeting with multiple-resources [56] and waste stream identification technique [57]. The CAT [12] has been extended to the Improved Problem Table (IPT) to locate flowrate targets for interplant hydrogen networks with direct reuse/recycle scheme [58]. The network targeting with multiple-resources and waste hydrogen stream identification can be easily performed in IPT [58]. However, the basis characteristics of hydrogen recovery for interplant hydrogen integration are lack of analysis. In addition, the targets for individual/interplant hydrogen network with the placement of purifier includes the minimum flowrates of hydrogen utility, feed and product flowrate of purifier and the optimal feed purity of purifier. There is a necessity to locate those targets via a generalized approach.

In this paper, IPT [59] is extended to be a generalized IPT to determine the flowrate targets of interplant hydrogen network with direct and purification reuse/recycle schemes. Two scenarios for direct reuse/recycle scheme are analyzed and LCCs and HSLs for individual hydrogen network are constructed. It aims to figure out the basic characteristics of hydrogen recovery for interplant