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Optimal design of inter-plant hydrogen networks with intermediate headers of purity and pressure

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ABSTRACT

This paper addresses the optimal design of inter-plant hydrogen networks with intermediate headers of purity and pressure. A superstructure for inter-plant integration of hydrogen networks is presented, where all hydrogen sources and hydrogen sinks are indirectly matched with each other through intra-plant hydrogen headers and inter-plant hydrogen headers. The corresponding mathematical programming model is constructed and a tailored two-step strategy is proposed to solve the model. In this solving method, the topology of the inter-plant hydrogen network and the purity levels of the hydrogen headers are first determined to minimize the cost of hydrogen utilities. The placements of compressors and pressure levels of hydrogen headers are then optimized to reach the lowest total annual cost of the inter-plant hydrogen network. The application of the proposed method is illustrated via a practical industrial case of inter-plant hydrogen network in China.

Introduction

Due to the increasing quantity of imported inferior and heavy crude and tighter environmental regulations on sulfide content in product oil, the refineries are forced to raise the processing capacities of hydrocracking and/or hydrotreating at the cost of a large amount of hydrogen [1]. The hydrogen deficit aggravates the fresh hydrogen shortage in refineries, making fresh hydrogen a more and more expensive resource for modern refineries [2]. Thus, efforts from the governments, industrial practitioners and scientists are urged to undertake effective measures to improve the efficiency of the hydrogen utilization and economical benefits [3]. The integration of hydrogen networks in refineries has hence been recognized as an effective tool to recover hydrogen and reduce cost of hydrogen plant [4].

The methodologies on the in-plant integration of hydrogen networks can be categorized into the insight-based pinch technique and superstructure-based mathematical programming approach. The former one usually involves a graphical/algebraic procedure to target the flowrate of hydrogen utility before looking into the detailed network design. Examples of these techniques include the hydrogen surplus diagram [5], hydrogen composite curves [6], problem tables [7] and cascade analysis [8] as well as their variants. Although these methods provide simple and intuitive procedures for flowrate targets of hydrogen network, they show certain difficulties in handling pressure constraints, multiple impurities and cost concerns [9]. In contrast, the abovementioned problems can be

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addressed by the superstructure-based mathematical programming approaches, and a comprehensive design of hydrogen network can be attained.

For the superstructure-based mathematical programming approaches, the problem of hydrogen network integration is generally formulated as a common optimization problem and can be solved in a simultaneous way or a stepwise manner. In these approaches, a superstructure model that accounts for all possible connections among different network elements is usually constructed, and a mathematical programming model determined by thermodynamic constraints and practical restrictions is often involved, aiming at the minimum hydrogen utility consumption [10], the lowest total annual cost [11], the minimum CO_2 emissions [12] and exergy consumption of hydrogen network [13]. These methods include the automated targeting method for direct reuse/recycle [14] and purification reuse [15], state-space superstructure method [16] and the superstructure-based formulation integrated with Sulphur removal [17] and vapor-liquid equilibrium [18], or with the considerations of temperature effects, physical properties and fuel gas specifications [19]. An extensive discussion on the existing hydrogen network integration techniques based on pinch analysis and mathematical programming can be found in recent review articles [1,2].

Compared with the in-plant integration, the inter-plant integration of hydrogen networks possesses superior advantages in the reduction of hydrogen utility consumption and total annual cost in industrial parks [7]. Three types of integration schemes, namely direct, indirect and mixed schemes have been developed for the inter-plant hydrogen networks. In a direct inter-plant integration scheme, the hydrogen sources and hydrogen sinks from different plants are matched via cross-plant pipelines, whereas they are integrated through a centralized purification units, such as pressure swing adsorption (PSA) or membrane separation in an indirect scheme. A mixed integration scheme is defined as a combination of the direct and indirect ones. Similar to the in-plant integration of hydrogen networks, both the insight-based pinch techniques and the superstructure-based mathematical programming methods have been presented to target the hydrogen utility and costs of inter-plant hydrogen networks with the above-mentioned three schemes. For example, the problem table has been improved to locate the flowrate targets of inter-plant hydrogen networks with direct reuse/recycle scheme [14], which was later extended to determine the flowrate target of inter-plant hydrogen network with purification reuse/recycle schemes [15]. The concentration cascade model was developed to design the inter-plant hydrogen network with a centralized purification unit [20]. Recently, a superstructure that is composed of hydrogen utility, hydrogen sources, hydrogen sinks, fuel system, compressors, purifiers and all possible connections among these elements, was presented in [9]. The corresponding mathematical programming model for the optimal design of inter-plant hydrogen network with the mixed integration scheme was also developed to target the minimum hydrogen utility and the lowest TAC. However, in these works, hydrogen sources are directly connected to hydrogen sinks for reuse/recycle with or without purification. The resulting network may thus be relatively complex, and any variations in hydrogen flowrates and purities of hydrogen sources may cause operational failure in meeting the requirements of hydrogen sinks.

In order to simplify the network configuration and enhance the controllability of hydrogen network, the intermediate headers could be properly used, as has been conducted in heat and water networks. In heat exchanger networks (HENs), the steam headers of different pressure levels are set to realize the matches between the heat sources and heat sinks in different plants so that the heat recovery is maximized [21] and/or the capital cost is minimized [22]. Analogy to HENs, multiple water mains of different concentration levels are also installed to collect and allocate the water streams in different water networks [23]. In this way, the fresh water targets and the operational flexibility can be reached [24]. However, it is worth noting that the design of hydrogen headers is more challenging than that of the steam headers and water mains because both the purity levels and pressure levels should be determined for hydrogen headers while only one property is required to be optimized for the steam headers (i.e. temperature or pressure) and the water mains (i.e. concentration).

We have also noticed that the in-plant integration of hydrogen network with internal headers has been explored in literature. Given a single hydrogen header, the improved problem tables has been used to locate the flowrate targets [25] and minimum compressor works [26] in hydrogen networks. Results showed that the flowrate of hydrogen header is related to its purity via a piecewise function. Jia [27] proposed a mathematical model including the mass balance for hydrogen header. However, the effects of the placement of hydrogen headers on structure of hydrogen network have not been well addressed [28]. To address this issue, Deng et al. [28] proposed a superstructure-based mathematical programming model for the synthesis of hydrogen network with one or two hydrogen headers of intermediate purity. Results showed that the flowrate of hydrogen utility decreases with the increase of the number of hydrogen headers. Zhang et al. [29] proposed a mathematical programming model to optimize the pressure levels of hydrogen headers according to the requirements of hydrogen sinks. However, in most of these works, the number of the headers are fixed to be one or two and only the purity levels are considered, little attention is paid to the number and pressure levels of hydrogen headers on the design of hydrogen networks. In addition, to the best of our knowledge, the inter-plant integration of hydrogen networks with both intra-plant headers and inter-plant headers has not been reported, and thus the effects of the placement and the properties of hydrogen headers, i.e. purity levels and pressure levels on the topological, operational and economical performance of intra-plant hydrogen networks and inter-plant hydrogen network have not been studied yet.

To solve these problems, a superstructure-based model for optimal design of inter-plant hydrogen networks with hydrogen headers of purity and pressure is proposed, where both the intra-plant headers and inter-plant headers are included. The optimal network topology and operational parameters of inter-plant hydrogen network corresponding to the lowest TAC are obtained. The effects of the placement and properties of hydrogen headers on the design of in-plant and inter-plant hydrogen networks are studied. The rest of this paper is organized as follows. A superstructure of the design

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