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An integration method for the refinery hydrogen network with coupling sink and source

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ABSTRACT

An integration method is developed for hydrogen network with the variation of the coupled sink and source considered. For sources or sink-tie-lines with different locations, the quantitative equations between the hydrogen utility adjustment and the coupled sink and source are deduced, and are simplified for the situations with the variations of the sulfur content of the material oil and inlet hydrogen. Based on this, the variations of the sulfur content, inlet hydrogen flow rate and inlet hydrogen purity versus hydrogen utility adjustment diagrams are built to analyze the effect of the corresponding parameters. The location and variation of the pinch point, the minimum hydrogen utility adjustment and the optimal inlet hydrogen are indicated by the far right broken line. The proposed method is simple and easy understanding. It can be applied to deal with the optimization problems of the hydrogen network with unfixed sink and/or source streams and analyze the effect of the inlet streams and operating parameters of the hydrogen consuming reactor, as shown by case study.

Introduction

Nowadays, the process of high-sulfur and heavier crude oil increases significantly, refiners need to increase their capacity of hydro-treating and hydro-cracking to produce high-quality products to satisfy the stricter environmental regulations. This results in the significant increase of hydrogen consumption. Decreasing the hydrogen consumption has become one of the most pressing concerns of oil refineries.

In refinery, most of the hydrogen is consumed by the hydro-treating and hydro-cracking reactors to control the products' sulfur content and provide the feedstock for the unit aims to produce ethylene, jet fuel and low freezing diesel. For a given hydrogen consuming reactor, to achieve the desired product and increase the conversion of the material oil, the inlet hydrogen is generally excess. Because of this, there is a lot of unreacted hydrogen in the outlet stream. For this kind of reactor, its inlet hydrogen stream is a sink, the hydrogen stream separated from its outlet stream is a hydrogen source. A hydrogen network includes multiple hydrogen sources and hydrogen sinks. The minimum hydrogen consumption can be achieved through integrating all the sinks and sources as a whole.

Researchers have done a lot of work in this region. Alves and Towler [1] found that the pinch exists in the hydrogen distribution network and developed an iterative graphical identification method. El-Halwagi [2,3], Zhao et al. [4], Saw et al. [5], Agrawal and Shenoy [6] developed different graphical methods to identify the pinch and minimum hydrogen utility

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without iterative calculation. Alwi et al. [7] developed the network allocation diagram to assist designers to select networks that yield either the minimum gas targets or the minimum number of streams. The water and property cascade analysis methods can also be applied to optimize the hydrogen distribution network [8,9].

Furthermore, purification has been considered in a lot of research. Alves [10] and Liu and Zhang [11] analyzed the possible placements of the purifier and concluded that placing the purifier across the pinch is the best choice. Foo and Manan [12] improved PCA to Gas Cascade Analysis (GCA) to solve the gas integration problem with purification. Ng et al. [13–16] proposed the pinch based automated approach to target the minimum utility consumption of the property and purity based conservation networks with regeneration/purification reuse. Liu et al. [17–19] developed the graphical method for identifying the upper bound of the purification feed and purified product, and their quantitative relationships with the hydrogen utility consumption. Zhang et al. [20] proposed a graphical method based upon the triangle representation of the purification. Yang et al. [21] extended this method to optimize the hydrogen network with the tail gas and purified product purity given.

However, most of the methods introduced above are proposed under the assumption that the networks are single-contaminant hydrogen networks. To target and design multiple-contaminant hydrogen networks, Zhao et al. [22] proposed an impurity deficit method based on constructing the contaminant profiles and contaminant deficit diagram. Based on ternary diagrams, Wang et al. [23] propose a new graphical procedure for minimizing utility consumption of multiple-contaminant hydrogen networks. Liu et al. [24] proposed an evolutionary method with matrix tools employed to design the resource allocation networks with multiple impurities. Zhang et al. [25] established a new ranking rule for identifying the reasonable order of streams, and developed an evolutionary graphical approach to target the minimum fresh resource demand and design the resource conservation networks with multiple contaminants.

Most of the methods introduced above are graphical methods based on the concept of pinch, a few are based on the algebraic method. The concepts and targeting processes of these methods are clear and comprehensive. However, as the number of contaminant increases, high-dimensional diagrams should be used, and it is difficult to represent the constraints of all contaminants graphically and target the hydrogen network. Scholars developed different mathematical programming methods for optimizing the hydrogen network. In these methods, the superstructure will be built, and the constraint on the composition/flow rate of each stream is expressed by a constraint equation/inequation instead of the graphical image representation. Hence, the constraint of each impurity/component can be considered easily and simultaneously. Besides, the compressors, purifiers, even uncertainty of the operating parameters, can be incorporated into the model and be optimized.

Hallale and Liu [26] presented a mathematical method with the pressure constraints and existing equipments accounted. Zhang et al. [27] presented an MINLP method for the overall refinery optimization considering the optimization of refinery liquid flows, hydrogen flows, and steam and power flows simultaneously. Van den Heever and Grossmann [28] presented a multi-period MINLP model for both the planning and scheduling levels. With the complexities of real refinery considered, Kumar et al. [29] developed a mathematical model to distinguish the optimum distribution of hydrogen. Jiao et al. [30] present a novel modeling and multi-objective optimization approach taking into account the flow rate constraints, pressure constraints, purity constraints, impurity constraints, payback period, etc. Zhou et al. [31] presents a systematic modeling methodology for the optimal synthesis of sustainable refinery hydrogen networks accounting for both the economic and the environmental aspect. Deng et al. [32,33] proposed two different superstructure-based mathematical programming models to synthesize the hydrogen network. One model can be applied to optimize the hydrogen network with the hydrogen intermediate header; the other can be applied to make a comparative analysis of several scenarios with the hydrogen utility, compressor, purifier and all the feasible interconnections considered. As different purification processes have different separation principles, Wu et al. [34] developed a unified model for different hydrogen purification processes. Liao et al. [35] presented a systematic approach for the integration of hydrogen networks with purifiers. Later, they developed a rigorous targeting approach with the pinch insight combined [36], and this method is extended to hydrogen networks with purification reuse [37]. Han et al. [38], Jiao et al. [39], Lou et al. [40] employed the robust optimization method to optimize hydrogen networks. There are also some other mathematical programming methods considering different constraints and optimization targets [26–28,41–46].

Due to uncertainty in the crude feedstock or final product specification in a refinery, there exists variations or uncertainties in the operating conditions (parameters) required for hydrogen network design. Jagannath et al. [47] develop a non-convex multi-scenario MINLP model to address the issue of optimal hydrogen network design under uncertainty or uncertain operating parameters. Jiao et al. [48] proposed a novel chance constrained programming (CCP) approach for the optimization of hydrogen network in refinery under uncertainties. Kuo and Chang [49] developed a shortcut calculation method to calculate the inlet and outlet flow rates and concentrations of hydrogen users and built an MINLP model for multi-period hydrogen network designs and considered the interaction between sources and sinks. Wang et al. [50] present a mathematical model to determine the optimal hydrogen network when the hydrogen demand varies.

Although the mathematical programming method can optimize the hydrogen network, this kind of methods cannot give clear insights about the integration process, as the mathematical model is generally solved by the black-box solver.

In a hydrogen network, a pair of sink and source connecting to the same reactor is coupled. There are multiple pairs of coupled sink and source streams. In practice, the inlet hydrogen stream of a hydrogen consuming reactor, which is a sink, can be varied in a certain purity and flow rate range, and its variation will affect the hydrogen consumption of the