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Hydrogen network retrofit via flexibility analysis: The steady-state flexibility index

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ABSTRACT

A systematic approach is presented to retrofit design of a hydrogen distribution network. A methodology is based on the steady-state flexibility index (FI_s) for optimizing network and enhancing the efficiency of purifiers. The main object of this technique is to investigate hydrogen network flexibility under severe operation uncertainty and to reduce streams to purifiers by consideration inlet feed purity of purifiers. The presented approach is applied to the hydrogen network of a real installation.

1. Introduction

The hydrogen system in a refinery provides hydrogen as fuels with cleaner specifications, for breaking down of heavier fuels, and as feed in other hydrocarbon processing operations. The rising cost of hydrogen and stricter environmental regulations have greatly motivated the management of hydrogen in refineries. The hydrogen management in hydrogen networks can be classified into two categories: pinch analysis methods and mathematical programming methods. Research in hydrogen network design through pinch analysis has included the targeting of minimum hydrogen utility consumption and network design (Towler et al., 1996; Alves, 1999; Alves and Towler, 2002; Zhao et al., 2006, 2007; Agrawal and Shenoy, 2006; Zhang et al., 2011; Liao et al., 2011a,b; Lou et al., 2013; Liu et al., 2013). These studies did not effectively deal with all possible practical constraints and/or adding new equipment as well as the optimal equipment emplacement and the optimal cost of network. Mathematical optimization approaches can be employed to consider these aspects of models. Some authors have addressed mathematical modeling for hydrogen network (Hallale and Liu, 2001; Liu and Zhang, 2004; Fonseca et al., 2008; Khajehpour et al., 2009; Ahmad et al., 2010; Kumar et al., 2010; Liao et al., 2010; Sardashti Birjandi and Shahraki, 2011; Jiao et al., 2011, 2012, 2013; Zhou et al., 2012, 2013; Sardashti Birjandi et al., 2014). The mathematical optimization approach has been developed to obtain optimal solution with more complex problems, improved design and hydrogen network integration and exploit hydrogen saving potential. For example, linear programming (LP) was utilized for optimization of hydrogen network by Alves (1999). Hallale and Liu (2001) developed mixed integer nonlinear programming (MINLP) approach to use pressure constraints in optimization of hydrogen network. Integration of hydrogen network includes design approach for selection of purification process proposed by Liu and Zhang (2004). Considering variables such as inlet and outlet pressure of compressors to obtain optimum solutions investigated by Hallale and Liu (2001). Ahmad et al. (2010) studied the

Abbreviations: LP, linear programming; NLP, nonlinear programming; MINLP, mixed integer nonlinear programming; MEN, mass exchanger network; PSA, pressure swing adsorption; LP OFF GAS, low pressure off-gases; HP OFF GAS, high pressure off-gases; RI, hydrogen recovery ratio to PSAI; RII, hydrogen recovery ratio to PSAII; ypI, product purity to PSAI; ypII, product purity to PSAII; yrI, residual purity to PASI; yrII, residual purity to PASII; yfI, feed purity to PSAI; yfII, feed purity to PSAII; LB, lower bound model; UB, upper bound model; M$, million $; M$/yr, million $/year.

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Nomenclature

C	Cost [$]
Cp	Heat capacity at constant pressure [J kg^{-1} K^{-1}]
D	Pipe diameter [m]
F	Flow rate [Nm^3/h]
P	Pressure [bar]
R	Hydrogen Recovery Ratio [–]
T	Temperature [K]
UP, LO	Upper and lower bounds of flow rate can be sent to new equipment [Nm^3/h]
y	Hydrogen purity [%]

Greek letters

ΔH_c	Heat of combustion [J Nm^{-3}]
$\in$	The cost of hydrogen [$/Nm^{-3}]
γ	Ratio of heat capacity at constant pressure to that at constant volume [–]
ρ	Density [kg m^{-3}]
η	Compressor efficiency [–]

Indices

i	Sources
j	Sinks

design of flexible hydrogen networks under multiple-period operation to improve networks. Sardashti Birjandi and Shahraki (2011) addressed an optimization of hydrogen network to use off-gases as the feedstock for steam reformer. Sardashti Birjandi et al. (2014) presented linearization technique and combination of the bound contraction procedure to solve MINLP/NLP models. Jiao et al. (2012) developed constrained programming model under uncertainty for hydrogen network optimization to achieve the profit and the probability of constraints violation.

In previous studies on the design of hydrogen networks and optimization of hydrogen distribution networks, it is often assumed that the process parameters are fixed and well-defined, but the actual operating conditions of networks may have various uncertain conditions such as those in feed qualities, product demands, and environmental conditions. Therefore, applying the analysis of operational flexibility in hydrogen network maintain feasible operation in the space of the uncertain parameters. In general, the term “flexibility” is considered as the capability of a process to function adequately over a given range of uncertain conditions (Chang et al., 2009; Riyanto and Chang, 2010; Li and Chang, 2011). Several publications have been reported for using the operational flexibility. The flexibility index is a well-established concept for quantitatively characterizing the ability of an existing process to cope with uncertain disturbances which proposed by Swaney and Grossmann (1985a,b). Later, Dimitriadis and Pistikopoulos (1995) introduced the dynamic flexibility index and the dynamic feasibility problem, which describe by sets of differential and algebraic equations and are subject to time-varying uncertainty.

The flexibility analysis has also been carried out in a series of subsequent studies to produce resilient grassroots and revamp designs. For example, Chang et al. (2009) proposed a nonlinear programming (NLP) model to account for flexibility index efficiently. They used a single critical point instead of the entire uncertain region in the parameter space, them the convergence rate of the optimization computation becomes much faster. Later, Riyanto and Chang (2010) proposed a heuristically strategy based on active constraints to improve the operation flexibility of existing water networks by inserting/deleting pipeline connections and adding/replacing treatment units.

A systematic flexibility assessment procedure was applied by Li and Chang (2011) to modify a given network to achieve the desired level of operational resiliency. The use of relaxing technique of the upper limit for freshwater capacity and/or adding new pipelines and/or removing existing pipelines to improve the operational feasibility of water network have been considered. The cases they studied were more based on the flexibility index model and the strategies for improving the operational flexibility in water network.

For hydrogen network it is possible to achieve the optimization of hydrogen network by using the flexibility index method and the existing strategies for improving the operational flexibility. First time, the concept of applying uncertain hydrogen demands from hydrogen consumers has been taken into account by Jiao et al. (2012). But, the operational flexibility strategies of how to modify hydrogen network have not been presented.

Therefore, the objective of this paper is to present flexibility assessment method for hydrogen network that will provide more network possibilities and total hydrogen sources satisfying varying hydrogen demands. Considering total allowed inlet streams purity that is sent to purifiers and using network structure, simplifications based on hydrogen flowrate purity will also be presented.

2. Problem statement

In hydrogen networks, there are several hydrogen producers and hydrogen consumers. The outlet streams of hydrogen producers, such as catalytic reforming unit and outlet off gases of hydrogen-consuming processes, are considered as hydrogen sources. The inlet streams of various hydrogen-consuming processes such as hydrotreaters and hydrocrackers are defined as hydrogen demands. Besides, purifiers and compressors should be considered as part of the hydrogen network.

The main goal of this study is to find an optimal design for hydrogen network based on the following two methods. The first method investigates efficiency increase of purifiers by considering inlet feed and its purity. Purifiers are usually employed to recover hydrogen from outlet off-gases from hydrogen consumers and the residue from the purifiers. Purifiers have the advantages of lower investment and operating costs as well as higher hydrogen purity, and have widely been used in hydrogen networks. The purifiers consist of one hydrogen sink (inlet feed and specified purity) and two hydrogen sources (the product stream of flow by a given purity and the residue stream of flow by a given purity). Then, it is desired to retrofit the hydrogen network and to increase efficiency of purifier while high purity hydrogen received in the inlet feed of purifiers.

In the second method the hydrogen network includes constants and uncertain parameters. For example, the flow rates of hydrogen sources, the throughput limits of purifiers, the hydrogen recovery and the upper bounds of hydrogen purity at the sinks are constant parameters and also the hydrogen source qualities, the mass loads of hydrogen-using units and their maximum allowable inlet and outlet hydrogen purity, the removal ratios of purifiers units and the upper bounds for their inlet hydrogen purity are uncertain parameters. The second method considers a set of systematic procedures to analyze and then to enhance the operational resiliency of any given hydrogen network design.

Thus, the aim is to show the hydrogen network retrofit with reducing streams with low purity of hydrogen sent to purifiers and also obtaining the corresponding uncertain region in the parameters domain. Application of the steady-state flexibility index (FI_S) for hydrogen network retrofit is based on the improved version of the flexibility index by Chang et al. (2009), Riyanto and Chang (2010), and Li and Chang (2011), in which the well-established concept of flexibility index is adopted for quantitatively characterizing the ability of a given water network to cope with uncertain disturbances.