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An MILP model for the reformation of natural gas pipeline networks with hydrogen injection

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ABSTRACT

A mixed integer linear programming (MILP) model is proposed for the reformation of natural gas pipelines. The model is based on the topology of existing pipelines, the load and pressure at each node and the design factors of the region and minimizes the annual substitution depreciation cost of pipelines, the annual construction depreciation cost of compressor stations and the operating cost of existing compressor stations. Considering the nonlinear pressure drop equations, the model is linearized by a piecewise method and solved by the Gurobi optimizer. Two cases of natural gas pipeline networks with hydrogen injection are presented. Several adjustments are applied to the original natural gas pipeline network to ensure that our design scheme can satisfy the safety and economic requirements of gas transportation. Thus, this work is likely to serve as a decision-support tool for the reformation of pipeline networks with hydrogen injection.

Introduction

The optimal design of natural gas pipeline networks is a widely examined topic at present [1–3]. Many natural gas pipeline networks have been built to date and cover a wide range of areas in many countries. To meet some new requirements of gas transmission, the reformation of pipeline networks will become an important issue. Blending hydrogen into existing natural gas pipeline networks is one such example. Many industries such as steel and caustic soda manufacturing generate large quantities of byproduct hydrogen each year. However, most of the hydrogen is released, resulting in a substantial waste of energy. In addition to byproduct hydrogen from industrial production, utilizing excess energy such as surplus wind electricity [4] and solar power [5] for the production of hydrogen is also an important source of hydrogen. The transportation and utilization of hydrogen is currently a prominent topic. Previous studies [6–9] have indicated that transporting a certain mole percent of hydrogen (4% (v/v) in Austria and 5% (v/v) in Germany [10]) through existing natural gas networks is

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technically feasible, but some unknown hazards are involved [11]. Moreover, due to the special physical and chemical properties of hydrogen, it can more easily damage pipeline materials and accelerate the failure of pipelines than can natural gas. Thus, in the design process, it is important to consider safety issues in pipeline networks. Many researchers have developed mixed integer linear programming (MILP) models to determine design plans [12–15]. Linear programming (LP) is a method used to find the optimal result of objective functions under a linear relationship, and MILP adds some integer and binary decision variables to LP. MILP problems are generally solved using a linear programming-based branch-and-bound algorithm; there are some state-of-the-art MILP model solvers, such as Gurobi [16].

To make better use of hydrogen and eliminate the impact on end users, technology for hydrogen recovery in a combined natural gas-hydrogen distribution network has been developed. In a project of Grainger et al. [17], relatively pure products (greater than 90 vol% hydrogen) could be separated from networks with low energy consumption. Liemberger et al. [10] proposed a hybrid approach to treat high-pressure mixtures of hydrogen and natural gas by membrane technology for pre-enrichment and pressure swing adsorption (PSA) for further improvements. The quality could reach 99.97% (v/v), and the energy consumption was low. In the NaturalHy project, executed by a European consortium of 39 partners, the aim is to mix hydrogen and natural gas for delivery in existing natural gas networks and withdraw the components selectively from the pipeline networks by advanced separation technology [18]. Considering the development of separation technology, the quality of natural gas and hydrogen provided to the end users will be better, and it could be possible to transport more hydrogen in the pipeline. Tzimas et al. [9] predicted that large sections of natural gas networks will be converted to or substituted with new pipelines to deliver hydrogen in the future. Therefore, to meet the safety requirements and avoid potential hazards, the operational plans of existing natural gas networks should be adjusted, and some pipelines will have to be substituted, when hydrogen is blended into the existing natural gas networks.

Many researchers have studied the transportation of hydrogen by existing natural gas pipelines. Tabkhi et al. [19] presented a model to evaluate natural gas pipeline networks under hydrogen injection and determine the pressure of the networks. The impact of hydrogen on the pressure drop through pipelines and compressors was studied, and the total sum of the fuel consumption in the compressors was taken as the objective. Ma and Spataru [20] established a model to analyze the economic and environmental influence of utilizing an existing natural gas pipeline network with different energy carriers such as hydrogen and biogas. Different scenarios were considered to evaluate the cost and environmental performance, and it was concluded that hydrogen was less expensive and that less CO_2 than biogas was produced. Hwangbo et al. [21] studied the integration of utility and biogas supply networks to produce hydrogen and established an MILP model to minimize the total annual costs of integrated utility and biogas supply networks and simultaneously satisfy hydrogen demand. Dickinson et al. [6] focused on the problem of utilizing remote renewable energy. Comparisons among a) converting remote renewable energy to fuel for transport using existing CNG pipelines, b) constructing new high-capacity electricity transmission lines, and c) directly injecting hydrogen into existing CNG pipelines were studied. Ogumerem et al. [22] presented a multiobjective MILP model to analyze a hydrogen supply chain network: the a) locations of the hydrogen facilities, b) production technology, c) size of each facility, d) transportation units, and e) distribution routes were determined. Mukherjee et al. [23] studied the problem of utilizing existing natural gas distribution and storage infrastructure to distribute and store electrolytic hydrogen. An MILP model without the use of buffer storage for hydrogen and an MILP model with storage were developed, and the economics were evaluated.

When hydrogen is blended, three main aspects of the network should be considered: the substitution of pipelines, the construction of compressor stations and the operating cost of existing compressor stations. We propose an MILP model and consider these three aspects simultaneously to minimize the reformation cost. Moreover, safety issues and hydraulic calculations are coupled in the model to ensure that the design process is reliable.

The remainder of this paper is organized as follows. Section Problem description describes the problem and states the data required, variables to be determined and assumptions. A model of how to optimize the transformation scheme of substituting pipelines, constructing new compressor stations and adjusting the operational scheme of compressor stations is provided in Section Mathematical model. In Section Case study, taking two cases as examples, the effectiveness of the method is verified, and the numerical results are given. Section Conclusion is the conclusion of this paper.

Problem description

This study focuses on the optimal reformation of existing natural gas pipeline networks with hydrogen injection. The natural gas pipeline network has several components, including pipelines, compressor stations, injection stations, and delivery stations. Considering the withdrawal of natural gas at each delivery station, the diameters of pipelines between stations can be different, which saves costs during the pipeline construction period. Although several problems are caused by mixing hydrogen in natural gas pipelines, such as hydrogen embrittlement [24] or hydrogen permeation [25], these problems can be overcome by increasing the yield stress and wall thickness of the pipeline. Moreover, using existing natural gas pipelines to transport hydrogen-natural gas blends is feasible [6–9]. When hydrogen is blended into existing natural gas pipeline networks, for safety reasons, the requirements for the yield stress and wall thickness of the pipeline should be higher. Thus, some problems may occur: 1) the operating pressure may exceed the maximum allowable pressure or the design pressure of some pipelines; and 2) the operating scheme of compressor stations may not adapt to the requirements of mixed-gas transportation. For safety considerations, some existing pipelines need to be substituted, some compressor stations may need to be constructed, and some existing compressor stations need to adjust their

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