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Evaluation of energy recovery and potential of hydrogen production in Iranian natural gas transmission network

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HIGHLIGHTS

- Formulation of a linear model that represent non-linear features of natural gas flow.
- Development of an optimization model for investment strategy of gas networks.
- Evaluation of energy recovery by turbo expander and ORC in natural gas networks.
- Evaluation of hydrogen production in natural gas supply networks.

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ABSTRACT

In the natural gas transmission network, from supply points to demand nods there are various technological options that include processing, transportation, conversion and gas distribution. Comprehensive analysis of natural gas network requires evaluation of different chains of gas flow through various levels based on economical and environmental criteria subject to technical and operational constraints such as feasibility, operability and reliability of different alternatives. To aid decision-making process in the sector of natural gas, a generic optimization-based model has been developed for assessing long term energy issues related to planning and design of natural gas supply systems. The model is capable of identifying optimal investment strategies and build up of new capacities of an integrated gas supply system. Evaluation of the potential of energy conservation and hydrogen production in transmission network are also investigated by three energy recovery technologies: turbo expander, ORC and electrolyzer. The model has then been applied in studying the development of Iranian natural gas network. The results indicate the utilization of produced hydrogen by electrolyzer has considerable impact on minimizing the total cost. The total produced hydrogen of the case study is 1337 million kg, in the period 2011–30.

1. Introduction

1.1. Background

Development and planning of natural gas transmission network involves capital intensive projects that have considerable impact on the energy economy in general and gas-rich countries (such as Iran) in particular. The investment costs and operation expenses of pipeline networks are extensive and marginal improvement in the system planning and utilization can substantially contribute to the economic efficiency of gas supply system (Azadeh et al., 2010; Dinca et al., 2007; Rios-Mercado et al., 2006).

Different aspects of the natural gas supply system have been analyzed in the past decades. The main elements of the network, that have been included in the previous studies, were gas pipelines and compressor stations and the objective has been minimization of the total costs i.e. investment and operational (Larson and Wong, 1968; Graham et al., 1971; Martch and McCall, 1972; Flanigan, 1972; Mah and Schacham, 1978; Cheesman, 1971).

Based on dynamic programming, Larson and Wong (1968) developed a steady-state model which considers a pipeline segment connected to a compressor station. Their model estimates the optimal suction and discharge pressure from pipeline. The length and diameter of the pipeline was assumed to be constant due to the limitation of dynamic programming.

Martch and McCall (1972) tried to modify the Larson and Wong model by considering a tree network. However, the transmission network was predestined because of the limitations of the optimization technique and assumption on constant pressure.

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Cheesman (1971) suggested an optimizing code to enhance the capability of the previous models by taking into account the pipeline variables such as length and diameter of a pipeline.

A mixed-integer nonlinear programming technique (MINLP) was introduced by Cobos-Zaleta and Rios-Mercado (2002) that minimizes fuel consumption in natural gas pipeline network. Decision variables in the MINLP were pressure at each node of network, the mass flow rate through the pipeline and the number of compressors to be installed within each station. The steady-state condition was assumed and the total supply flow was driven completely to meet the demand for natural gas with no loss along the network. The model was only capable of solving small problems for specific type of compressor units.

Rios-Mercado et al. (2006), proposed a heuristic solution procedure where the fuel cost is minimized within a cyclic network topology. It means that a network containing at least one cycle with two or more compressor stations. The procedure included two stages. At the first stage, gas flow was assumed constant and optimal pressure was estimated. At the following stage, pressure was kept constant and an attempt was made to calculate the rate of flow that might improve the objective function. Their model was appropriate for both cyclic and non-cyclic network but it was considerably cumbersome to solve a cyclic network.

Kabirian and Hemmati (2007), developed an integer nonlinear programming in order to identify an optimal expansion plan of an existing natural gas network. The minimization of total costs of the network was considered as the objective function. The main outputs of the model have been reported to be type, location and installation schedule of pipelines and compression stations.

A review of the existing analytical tools indicates that processing plants and transport units, such as pipeline segments and compressor stations, are considered in the above mentioned studies. Despite the improvement in the modeling of the gas transmission network, it may be concluded that technological options for enhancing energy efficiency at the transport and distribution levels have rarely been considered. But it is to be noted that energy loss in the compressor stations and pressure reduction valves at the distribution level is considerable and it is a determining factor of energy efficiency of natural gas network. Various technological options have been developed for recovery of energy losses in the natural network such as turbo expander and the organic rankine cycle system (ORCs) (Pozivil, 2004; Maddaloni and Rowe, 2007; Desai et al., 2009; Wang et al., 2011). A system of turbo expander is a substitute for the reduction valves in gas pressure reduction stations (GPRSs). And the ORC system retrieves thermal energy from high temperature exhaust gases of gas turbines employed in the gas pressure compression stations (GPCSs). The recovered energy is now available as electricity which can be sold to the grid or used in a local process. The next option is using the previous wasted energy to produce hydrogen gas, compressed and stored, ready for dispensing. Of course, hydrogen infrastructure developments will be worthwhile only if the hydrogen is produced in a sustainable way. This means that the production has to be based on efficient conversion technologies in the proper scale. The advanced hydrogen production technologies are natural gas steam reforming, reforming of fossil fuels, partial oxidation of heavy hydrocarbons and electrolysis (Miltner et al., 2010; Liao et al., 2010). In this study, electrolysis of water is considered as technology for the production of hydrogen, because it is only technology which is fed by electricity. The hydrogen production by electrolysis was widely investigated previously (Grigoriev et al., 2006; Marshall et al., 2007; Jomard et al., 2008; Wrana et al., 2010; Zeng and Zhang, 2010).

Behavior of a turbo expander in GPRS has been modeled by Pozivil (2004) using the HYSIS environment. The model consisted of steady-state calculations based on the isentropic efficiency of a turbo expander. The simulation was carried out at a variety of presumed inlet and outlet conditions and isentropic efficiencies. The model output included generation of electric power, preheating requirements and thermal efficiencies.

Maddaloni and Rowe (2007) also investigated utilizing a turbo expander in pressure reduction station to produce electricity. The electricity can either be routed back into the electric distribution grid or used to produce small amounts of hydrogen.

In addition to the turbo expander, heat recovery in turbo-compressor stations provides a technological option for improving energy efficiency of gas transport network. Heat recovery through utilization of ORC is a viable option which could be considered. Desai et al. (2009), proposed a methodology for optimizing the operation of an ORC for 16 different organic fluids. They have reported 16.5% improvement in the thermal efficiency of an ORC system.

Based on thermodynamic model, Wang et al. (2011) examined the performance of 9 different organic fluids at fixed net output power. The thermal efficiency of an ORC with various working fluids was examined based on application of different evaporating pressures and condensing temperatures.

1.2. *Further development of model*

The modeling approaches in the referred studies can be classified according to the techniques used in these analytical tools, such as optimization, simulation, non-linear, linear, static and dynamic. Linear optimization is applied to identify the optimal design or operation of the system. Nonlinear programming problems are constrained optimization problems with nonlinear objective and/or constraint functions. A disadvantage of nonlinear programming over linear programming is that general purpose program is somewhat less effective because the nonlinear paradigm encompasses such a wide range of problems with a great number of potential pathologies and eccentricities. In the sense that certain active constraints become dependent, or are only weakly active. Curvature in the objective or constraint functions (a second-order effect not present in linear programming), and differences in this curvature between different directions, can hinder identification of global optimal point, especially when second derivative information is not supplied by the user or not exploited by the algorithm.

A static solution procedure usually assumes a fixed gas demand for a single pathway. The static approach is simple and therefore widely adopted, but has significant restrictions when it is applied for analysis of gas pressure drop within a pipeline segment. Indeed it disregards changes of gas pressure in pipe segments. The static approach, with or without optimization, is inaccurate because it ignores the financial and technical effect of evolving factors (such as gas demand and techno-economic parameters of technologies) on the supply side.

Dynamic approaches consider the dynamic changes in the infrastructure over time and how transport from one pathway to another should take place as market conditions change.

The dynamic resource allocation problem is an extension of the static problem for finding the optimal allocation of a specific resource to a certain demand at each time period. Since natural gas network is composed of various systems and related energy recovery technologies are novel, a dynamic analysis of the long-term development of gas supply system is vital.

Based on the above conclusion, model GNM (Gas Network Model) has been developed in the present research work which shall be described in the present paper. GNM is a dynamic and linear optimization-model which avails itself to long-run planning of the development of natural gas supply system. All supply and