Energy 125 (2017) 848–859

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Optimization of a natural gas distribution network with potential future extensions

Markéta Mikolajková*, Carl Haikarainen, Henrik Saxén, Frank Pettersson

Thermal and Flow Engineering Laboratory, Åbo Akademi University, Biskopsgatan 8, Åbo, 20500, Finland

A R T I C L E I N F O

Article history:
Received 17 December 2015
Received in revised form
6 October 2016
Accepted 15 November 2016
Available online 29 January 2017

Keywords:
Natural gas network
Systems optimization
MINLP
LNG

A B S T R A C T

A model of a pipeline network for gas distribution is developed considering supply of gas, either from external gas networks or as injected biogas or gasified liquefied natural gas (LNG) at terminals. The model is based on mass and energy balance equations for the network nodes, equations of the pressure drop of a compressible gas in the pipes, as well as expressions of gas compression in compressor nodes. The model is applied within an optimization framework where the optimal supply of natural gas to the customers is studied under a multi-period mixed integer nonlinear programming (MINLP) formulation, considering possible extensions of the pipeline network to new sites as well as potential supply of the gas from LNG terminals. The natural gas network in Finland is used in a case study, which determines the network's size and operation conditions. The results illustrate that the model can tackle complex gas supply problems and that it finds interesting alternatives where the optimal gas flow is reversed between the periods. The findings reveal the conditions under which it is beneficial to upgrade existing connections by parallel pipelines, extend the pipeline to new sites, or to re-gasify LNG and inject it into the network.

1. Introduction

Natural gas is an energy source of growing popularity because of the exploitation of new gas resources in combination with its lower environmental impact compared to oil and coal. The growing market for liquefied natural gas (LNG) has made this energy resource available at new sites. In 2014 the natural gas consumption in Europe was about 14,400,000 TJ [1]. The planning and construction of LNG ports in Europe, such as the new LNG port in Świnoujście, will make it possible to increase the capacity of the gas storages and the transported volumes in the future [2]. Therefore, it is becoming important to explore the option of combining natural gas available via pipelines with gasified LNG from storage terminals available at the coastal region. This potential interplay between gas sources is intricate, as gas may be transported in different directions during different periods, depending on costs and availability, making the design and efficient operation of such a networks a challenging task.

Natural gas is currently delivered to Finland from Russia through a double pipeline connection to the city of Imatra in eastern Finland. The transmission pipeline distributes the gas further to the southern parts of the country to customers that are predominantly heat producers, but also include power plants, large industries or households. The annual natural gas consumption in Finland has been about 30 TWh [3] and recently it has been decided that a pipeline connection between Finland and Estonia should be built. This would allow for increase in the volume of natural gas supplied to Finland and to new customers, simultaneously improving the energy security of Finland. Smaller LNG terminals have also been planned in Finland and two are currently being built at the Finnish coastline. To assess such future scenarios, it is important to be able to study the potential gas distribution systems by simulation and optimization.

Pipeline delivery of natural gas has attracted attention in the scientific community in the past. The approaches how to solve the steady-state gas transmission problem can be generally differentiated by the algorithm used. The problem can be either reduced to a linear problem that is easily solved, or be formulated as an MINLP problem considering both nonlinearities and structural aspects of the network. The increased complexity of the problem including the problem formulation (LP, NLP, MINLP) and the topography of the natural gas pipeline (linear, tree or circular) influence the

* Corresponding author.
E-mail address: mmikolaj@abo.fi (M. Mikolajková).

http://dx.doi.org/10.1016/j.energy.2016.11.090
0360-5442/

computational demands and solution time to a large extent [4]. The costs that have been included in the objective function also vary: Costs often included are investment, operational or cost of compression. Also the way how the investigators account for the costs is different and more recently costs related to CO_2 emissions have also been considered. Due to the large computational demands the approaches in the earlier stages were often based on NLP formulations. In their early work, Wong and Larsson solved an NLP problem of natural gas pipeline distribution by minimizing the compressor fuel cost with the help of dynamic programming [5]. A similar formulation was applied by Králík et al. [6], who later developed a software used for the simulation of the dynamic behavior of gas distribution in large natural gas networks. De Wolf and Smeers proposed a solution of the optimal dimensioning of a gas transmission network problem by separating the solution procedure into two stages [7] and developed an extended simplex algorithm to solve the cost minimization problem with the help of piecewise linearization [8]. A natural gas distribution problem as stated by de Wolf and Smeers was also studied by Bakhouya and de Wolf, focusing on minimum fuel consumption in the compressors, which corresponds to the lowest energy needed for the gas transportation. These authors later dealt with the changes on the gas market by separating the transportation function and gas buying function while minimizing the energy of gas transportation [9]. Kalvelagen re-stated the problem posed by de Wolf and Smeers as a Discrete Nonlinear Programming (DNLP) problem and solved it with the GAMS software [10]. Borraz-Sanchéz and Haugland tackled the problem by minimizing fuel cost in gas transmission networks with the help of a dynamic programming approach [11], later complemented by a study of the influence of gas density and compressibility on the gas flow [12]. Möller et al. [13] suggested an MILP formulation using the sub-polyhedra linking the piecewise linearization used for the minimization of the compressor fuel consumption. Although the MILP formulation offers more efficient algorithms that guarantee global optimality, yet the accuracy of some non-linear relations may be lost through the linearization and the number of binary variables also increases. An MINLP formulation of the gas transportation problem which mainly addressed the minimization of the fuel consumption in the compressor stations was presented by Cobos-Zaletta and Ríos-Mercado [14], but the investigators did not consider the possibility of altering the gas flow directions.

Because of the nonlinearity and complexity of the MINLP formulation of the problem, meta-heuristic approaches have been suggested to solve the natural gas transportation task, e.g., ant colony optimization [15]. Tabu search as a meta-heuristic solution to the problem was presented by Borraz-Sánchez and Ríos-Mercado [16]. Genetic algorithms (GA) can be used to extend the minimization of the cost problem by adding multiple objective functions such as the maximization of the gas flow and line pack together with the minimization of CO_2 emissions, as illustrated by Alinia Kashani and Molaei [17]. One of the largest problems of these optimization techniques is the number of assumptions that are made in order to solve the problem, some of which may be rather restrictive [4]: It can be quite difficult to obtain reliable results if the gas transmission problem is approximated by simplified equations. For that reason, MohamadiBaghmolaei et al. [18] suggested to use Artificial Neural Networks (ANN) incorporated in a GA to solve a problem that to a large extent was based on experimental data. The stochastic behavior of the demand was furthermore tackled by Fasihizadeh et al. [19] by using simulation to guide an optimization of the pipeline network. This was done with the SIMONE simulation software developed by Králík et al. [6] A similar approach was made by Szoplik [20] using the GasNet software to study the relationship between pressure and gas stream in an existing pipeline network. Another approach targeting especially the operational costs element related to the compressor operation in the optimization process is the Nonlinear Model Predictive Control (NMPC) derived by Gopalakrishnan and Biegler [21]. Recently, attention has been shifted from the solution of the gas flow in a pipeline towards the optimization of the gas marketing and trade problem. The impact of the market price on the natural gas network structure was investigated by Lochner and Dieckhörner [22], complementing the work of Lochner [23] who studied the influence of bottlenecks and cost of congestion on the network structure. Fügenschuh et al. [24] examined the impact of the liberalisation of the market on the network structure and suggest a prototypical solution to this problem.

Even though many of the investigations referred to above have tackled the problem of optimizing gas distribution networks, the approaches have been based either on rigorous optimization using simplified models or optimization using manual or hybrid approaches with more detailed simulation models. In the work of the present paper, a detailed nonlinear model [25] was optimized using a rigorous approach, i.e., mixed integer nonlinear programming (MINLP). By contrast to earlier work, this model allows for the use of non-linear expressions, changes in the gas flow direction between the time periods studied, as well as decision about whether or not to connect new supply or demand points. By considering these features, future operation and extension options for an existing gas distribution system can be assessed. The feasibility and features of the model are illustrated by tackling the problem of determining the optimum connections and state of operation of the future natural gas grid in Finland, with possible extension of the existing pipeline to new consumers, as well as inclusion of gas supply points (LNG terminals with regasification). The results of the analysis can be used to support future decisions concerning the development of the gas supply chain and the best operating practice of the gas distribution system.

The paper is organized as follows: Section 2 presents the main assumptions behind the mathematical model as well as the resulting equations, including the economic objective function to be minimized and a brief presentation of the software used to solve the problem. Section 3 presents the background of the case study and some results of the model applied to optimize the problem at hand. Finally, the last section presents conclusions and proposes some ideas of forthcoming work in the field.

2. Mathematical model

2.1. Basic assumptions

A model of a transmission pipeline network of natural gas was developed with the following assumptions, partly illustrated in the schematic of Fig. 1. Gas transportation in steady state in the system is described by expressing the flow between nodes $i, j \in I$, in some of which a demand is specified. Nodes can be connected by pipes of different types, $r \in R$ and length $l_{i,j}$. Certain nodes may have a gas supply, i.e., be connected to gas resources outside the system boundary by pipeline, or represent a re-gasification site. Nodes may be connected by single or parallel pipelines, but the flow is unidirectional during each period considered. A set of compressors are placed along the pipeline, each containing a suction ($i \in I_{suc}$) and a discharge node ($i \in I_{dis}$) connected so the flow can be realized in both directions. All of the nodes representing the demand points can both send and receive gas, but the suction point in the compressor can only receive gas from the network and the discharge node can only send gas further to the network.

The demand may vary, e.g., with the season, but must always be satisfied by gas, an alternative fuel, or as a combination of both.