Design and dimensioning of natural gas pipelines with hydrogen injection

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1 Introduction

The current level of atmospheric pollution in the world, as well as the dependence on fossil fuels, has given rise to global commitments and public policies aimed at mitigating the damage caused, mainly seeking to reduce emissions of polluting gases, for which the objective is to change the energy matrix centered on fossil fuels in favor of renewable energies. Among them, hydrogen stands out, not only because of its energy capacity, which exceeds that of hydrocarbon fuels without emitting CO2 during combustion, but also because it would allow regulating the production of electricity when produced by electrolysis of water with surplus electricity, which would allow storing it for later use. Although the benefits of hydrogen are numerous, it is not currently likely to dominate the fuel market, largely due to uncertainty about government policies and regulations, consumer acceptance, and lack of infrastructure.

Thus, many authors have proposed to address the optimal design of these facilities [3]. On one hand, some researchers have opted for the design of a complete supply chain, considering different parts of this system[5, 4, 2]. On the other hand, some authors have centered on specific components of the hydrogen supply chain, such as transportation and distribution, focusing their studies on the optimal design of pipeline networks mainly through nonlinear models, solved by means of heuristics or linear relaxations. Based on this, our proposal seeks to complement existing studies, addressing the design and sizing of natural gas pipelines with hydrogen injection problem, considering discrete diameters under an exact resolution approach.

2 Mathematical Formulation

The problem of designing and sizing a hydrogen injection pipeline network is to find both a network topology and the diameter dimension of each pipe section for hydrogen distribution. Formally, given a digraph $G = (N, A)$, where N is the set of hydrogen supply and consumption nodes and A is the set of potential links through the hydrogen pipelines, we define a pipeline network topology as the connected subgraph $G' = (N, A')$ induced by a set of arcs $A' \subset A$. Each node has a demand or a quantity of hydrogen that can supply. The aim is to minimize the cost of building pipelines and distributing hydrogen, so that the proposed network can meet customer demand. The flow of hydrogen in the network is governed by the physical quantities related by the equation of fluid mechanics :

$$(\pi_1 - \pi_2)D^5 = k'Q^2L \tag{1}$$

where π_1 and π_2 represent the square of the pressure at the inlet and outlet of a pipe, D and L are the diameter and length of the pipe respectively, and Q is the quantity of gas flowing in the pipe. Finally, k' is a constant.

Due to the form of equation (1), the mathematical models representing this problem are complex because they include polynomial terms up to degree 6, as well as some integer variables. In this study, we consider two perspectives for pipe diameters, first the continuous diameter perspective, where pipe diameters can take any value within a given minimum and maximum, and the discrete diameter perspective, where pipe diameters can take only a few possible values. The latter is a realistic assumption whose first effect is to increase the number of integer variables in the models. But it also allows us to reformulate the degree-6 polynomial model into a quadratic one. The resulting model is thus a quadratically constrained quadratic problem with binary variables. We also show that its continuous relaxation is equivalent to a convex optimization problem. Finally, fixing the topology network to an arborescence in this model leads to a mixed-integer linear problem and gives rise to fast heuristics.

3 Numerical Experiments

We implement the global solution method based on our discrete-diameter models, together with heuristics. We then compare our results with existing solution methods on randomly generated instances and on a case study in France based on realistic data from [1] with up to 78 demand nodes. Although discrete diameter models are slower than continuous diameter models, through the exact resolution of our discrete diameter model we were able to find a feasible solution to the problem with a final gap of 9%, where the network found presents a cost saving of up to 30% with respect to all other methodologies.

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