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Steady-state flow computation in gas distribution networks with multiple pressure levels

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ABSTRACT

Natural gas networks are critical lifelines essential to the continued well-being of a community. Whatever its scope, the analysis of a gas network cannot rely on simple connectivity methods: limited tolerance on quantity and quality (pressure) to maintain serviceability to end-users generates the need for a flow analysis. Scarceness of the literature on flow analysis for gas networks and limitations of the available methods prompted this work. A novel complete steady-state flow formulation is reported, up to the governing nonlinear system of equations and the expression of the error function to be minimised to find the solution. Important features, such as the correction for elevation change in pipes and the pressure-driven mode, are included. The possibility to treat multiple pressure levels, as is the case of real networks, represents the main novelty of this work. The presented procedure was coded into a programming language and applied to several test cases, one of which being a non-trivial realistic gas network with 67 nodes and 88 edges. Such examples served the purpose to validate the formulation and to show its computational performance in the presence of multiple pressure levels.

1. Introduction

Natural Gas (NG) is today considered the cleaner alternative among fossil fuels, thanks to the reduced emissions of greenhouse gases [1]. For this reason, its global consumption worldwide is growing, and is expected to double by 2030 [2]. The transportation of large quantities of NG (referred to as "gas" hereafter) across countries and regions is carried out by pipeline networks. Gas networks, together with other *Critical Infrastructure* (CI) systems, such as power, water, transportation (road, railway) and communication networks, are *lifelines* essential to the continued well-being of a modern community. These CI systems are characterised by multiple mutual interactions. Gas networks have strong links especially with electric power networks and buildings. An appropriate analysis of a gas distribution network is crucial when the analysis scope is not just this network, but the entire set of interacting CI systems and buildings of an urban area [3].

As for other networks, the behaviour of a gas network can be represented in terms of topological, *connectivity analysis* or of a more refined *flow analysis*; the latter includes connectivity and involves computation of the system's operational state, in terms of node pressures and edge flows. Similarly to electric power networks [4], the low tolerance on amount and quality, in terms of pressure, of gas fed to end-users for maintaining serviceability often results in connectivity-based methods to be unsuitable for the analysis of gas systems. For flow analysis of gas networks and other lifelines, most researchers and practitioners employ commercial and non-commercial (open-source) software packages. Examples are given by SynerGEE for gas networks [5], ERACS and EDSA for power networks [6], EPANET for water supply systems [7], and FLO-2D for natural storm water systems [8]. Most of these tools focus only on one network and rarely allow an analysis of multiple interdependent lifelines, despite the strong interactions existing between systems of modern infrastructures. Further, commercial tools are closed programs used as black boxes, and cannot be expanded or modified to meet the increasing needs of researchers.

The goal of this paper is to provide a complete formulation of the steady-state flow analysis of a gas distribution network, thus providing an important contribution to this field. The algorithm was implemented within an open source simulation tool for civil infrastructures, namely Object-Oriented Framework for Infrastructure Modelling and Simulation (OOFIMS) [3,9], recently developed within the European project SYNER-G (2012) [10] and able to handle system interdependencies.

Despite the importance of flow analysis, current literature

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features only a few works on flow computation in gas systems. Osiadacz and Pienkosz [11] provide the more detailed flow computation algorithm for gas systems, which, however, has limitations that will be highlighted in the following. An interesting document on the subject is the thesis by Hwee [12], presenting a number of flow equations in use for gas networks, as well as simple examples that were used here to validate the new proposed algorithm. Abeysekera et al. [13] investigate the impact of using different gas supply sources on pressure distribution and gas quality within a network, making use of a flow analysis along the lines of Hwee [12]. A further paper focussing on the subject is that by Morais and Lima [14]. Other papers found in the literature are related to specific aspects of the flow formulation, and will be referred to within the following sections.

To the best of the author's knowledge, all methods available in the current literature on flow computation for gas networks are limited to a single pressure level. On the other hand, multiple levels in other lifelines are treated differently from gas networks: for instance, the presence of multiple voltage levels in electric power networks is handled with specific equations for transformers, and the methodology cannot be used for pressure reduction in gas systems. The formulation presented in this work fills one gap in the literature, allowing for the computation of gas flows in the presence of multiple pressure levels. This feature is of paramount importance in the analysis of real gas systems and specifically in the treatment of assessment problems, where a network cannot be decomposed in pressure-homogeneous portions to be solved independently. This advancement represents the main novelty of this work.

The second important novelty stands in the application of two features of the methodology, namely the correction for elevation change in pipes and the pressure-driven formulation, which were found in the literature but never applied to case studies. Pressure-driven formulation, analogue to the head-driven formulation of water supply networks, is essential in a network assessment problem where, contrary to the situation of a design problem, there is no assurance that demands will be satisfied and allowance must be made for gas not reaching an end-user due to excessive depressurisation along the network; this is the case, for example, of gas networks affected by earthquake-induced damage [15].

Finally, all referenced papers present small "academic" examples, whereas the algorithm implemented here was applied to a non-trivial realistic gas network composed of 67 nodes and 88 edges, thus resulting to be computationally effective and hence usable within simulation schemes for risk assessment (see e.g. Ref. [16]).

The remaining sections of this article are organised as follows. In Section 2, the taxonomy of gas distribution networks is briefly outlined, limited to the aspects of interest for the paper. Section 3 presents the steady-state flow formulation, up to the definition of the error function to be minimised in order to obtain the solution. In Section 4, the implemented formulation is validated and applied to four examples of increasing complexity, through which all the discussed features are highlighted. Conclusions and future work are reported in Section 5.

2. Taxonomy of gas networks

Gas is supplied across a country through several networks operating at different pressures. A national transmission system conveys gas from the sources to the different regions of the country, where it is passed to regional transmission systems operating at lower pressures. For local conveyance of gas to end-users, the distribution system is used. The pressure level makes the main difference between transmission and distribution systems. The former operate at high pressures (>7 bar), while the latter operate at medium (75 mbar–7 bar) and low (<75 mbar) pressures [17]. In this paper, the focus is only on distribution (both low and medium pressure) networks.

A gas distribution network is a graph made up of nodes and edges. The graph is typically undirected (an edge between nodes i and j implies the existence of the opposite one, between j and i), since the flow direction is not known *a priori* (i.e., before running a flow analysis) and flow in pipes is allowed in both directions. Nodes may be stations, demand (or load) nodes (where gas is delivered to end-users, typically at low pressure) and joints.

Three main types of stations may exist [15]:

1 Metering/Reduction (M/R) stations, which contain metering equipment for monitoring gas flow, as well as pressure reduction equipment. In M/R stations gas is derived from the high pressure transmission network and injected into the medium pressure distribution network, for which such nodes function as source nodes;
2 Reduction Groups (RGs), which are stations operating pressure reduction between medium and low pressure, or between two medium or low pressure levels. RGs may also serve as load nodes and deliver gas at medium pressure to industrial users, and in this case are called RGMs (Reduction Groups and Metering);
3 Metering stations, which are only flow measurement points.

The edges between nodes are buried pipelines. The most common employed materials are steel, polyethylene (high-density, HDPE, or low-density, LDPE), ductile iron and copper [17].

3. Steady-state flow formulation

The topology of a graph with n nodes and m edges is described by the $n \times m$ *node-edge incidence matrix*, $\boldsymbol{A}$, such that:

$$A_{ij} = \begin{cases} +1, & \text{if the flow in edge } j \text{ leaves node } i \\ -1, & \text{if the flow in edge } j \text{ enters node } i \\ 0, & \text{if edge } j \text{ is not incident to node } i \end{cases} \tag{1}$$

3.1. Kirchhoff's laws

Kirchhoff's first law is the principle of conservation of mass. It states that the algebraic sum of flows in a network of edges meeting at a point is zero, or, equivalently, at any node in a graph, the sum of ingoing flows equals the sum of outgoing flows. By defining n_2 as the number of source nodes in the network, it is possible to write Kirchhoff's first law in the following matrix form [11]:

$$\boldsymbol{A}_1 \cdot \boldsymbol{q} = -\boldsymbol{Q} \tag{2}$$

where $\boldsymbol{A}_1$ is the $(n\text{-}n_2) \times m$ matrix whose rows are related to load nodes (and thus obtained by deleting the rows of $\boldsymbol{A}$ related to source nodes), $\boldsymbol{q}$ is the $m \times 1$ vector collecting the edge (or pipe) flows and $\boldsymbol{Q}$ is the $(n\text{-}n_2) \times 1$ vector of node loads (i.e., the demands).

Kirchhoff's second law is the principle of conservation of energy. It states that the pressure drop around any closed loop is zero. This law can be expressed in the following matrix form [11]:

$$\boldsymbol{A}^T \cdot \boldsymbol{P} = \Delta \boldsymbol{P} \tag{3}$$

where $\boldsymbol{P}$ is a $n \times 1$ vector whose generic element, P_i (i.e., the one related to node i), equals the pressure at node i, p_i, for low pressure nodes, and the pressure at node i squared, p_i^2, for medium pressure