Topological modelling of gas networks for co-simulation applications in multi-energy systems

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Abstract

This paper focuses on the modeling and simulation of gas networks to be used in an integrated multi-carrier energy scenario. A topological approach is followed, where a simplified graph-based description of the gas network is adopted and a systematic analysis of the metrics of three real test cases is carried out with the aim of discovering relevant network features. The governing equations of the basic building blocks such as pipelines, compressors and pressure reduction stations are readily derived under the assumptions of steady-state operation and isothermal behavior, allowing a good matching between model compactness and accuracy. In addition, a circuit-based interpretation of model equations and well-established tools for circuit analysis are used. The obtained results proved that the proposed approach offers a feasible tool for gas networks, which can be readily integrated in a co-simulation framework.

Keywords: gas networks, steady state analysis, graph-based network models, network topology.

1 Introduction

As the installed capacity of non-dispatchable renewable energy sources (RES) constantly grows worldwide, energy infrastructures face several technical challenges to maintain certain levels of reliability. The case of California Independent System Operator [1] and many other case studies in the literature clearly show that power systems will increasingly need to rely on flexible solutions to accommodate large shares of intermittent RES generation.

It is well acknowledged that renewables will cause thermoelectric utilities to growingly operate under variable conditions, and related aspects have been analyzed and quantified by several papers, among which [2,3], under different scenarios of RES penetration.

Today, one of the first-choice flexibility options for power systems is constituted by gas-fired power plants, due to their shorter start-up times, higher ramping capabilities and lower CO_2 emissions compared to other conventional technologies. It is straightforward to question whether more frequent and severe changes in the gas demand of gas-fired utilities can therefore have repercussions on the stability of the gas network and on the reliability of the gas supply. At present time, these aspects already pose real concerns for system operators [1,4]; several papers have also been developed around these issues, proposing methodologies for co-simulating integrated electricity and gas networks making use of detailed physical models of the infrastructures [5,6].

In other words, the discontinuity of RES impacts beyond the only power grid, affecting also the gas networks and causing more frequent and severe transients during its operation. Nevertheless, recent contributions show that the gas-electricity nexus is made up also of significant opportunities. Specific technologies, such as power-to-gas (P2G), may provide a strategic link between the power grid and the gas network, allowing for less frequent curtailments of RES and decarbonizing other sectors different from electricity, like heating or transport. The grid injection of hydrogen produced from excess renewable power through electrolysis makes of the gas network a bulk storage option and enhances its role of power back-up for gas-fired power plants [5,7,8]. Notably, power-to-gas may provide solutions for mitigating power network congestion, deploying hydrogen or other synthetic gases as energy carriers in gas pipelines.

In this perspective, the deep transformation of the power sector opens new horizons for the utilization of the gas transportation infrastructures, which could lead to relevant technical and cross-sectorial benefits in terms of flexibility, resilience and efficiency of the energy systems.

From these considerations, it follows that future (and current) multi-carrier energy systems should unavoidably be studied in an integrated fashion, where the co-simulation of different infrastructures represents an essential approach for obtaining meaningful results.

Research on coupled energy networks relies on the availability of 1) computational tools for the physical modelling and simulation of the infrastructures and 2) case studies, i.e. network structures, to be analyzed. The number of case studies should possibly be large enough to generalize simulation results. In this regard, there exist a number of standard and real-world power grids from publicly available sources. Also, a number of topological models and tools for the generation of random networks with realistic structural properties have been proposed for both transmission and distribution systems [9–11]. On the other hand, data accessibility for gas networks is overall very limited, while topological analysis on gas transportation systems have been mostly devoted to assessing the system vulnerability to failures or supply interruptions [12]. Therefore, the development of tools for the generation of synthetic models of gas networks with realistic properties is of topical interest for overcoming this gap.

Based on the above considerations, the present work illustrates a solution for the simulation of gas networks which combines accuracy and model compactness, thus constituting an efficient alternative more rigorous physical-based approaches. We present a graph-based modelling technique for network components (including non-pipeline elements) complemented by a circuit-inspired solution method which fully benefits from this representation. Results are illustrated for a real case study, including a validation carried out via a comparison with the literature and other simulation tools. The above-mentioned modelling aspect is complemented by an systematic structural analysis of real networks, carried out with the aim of discovering key topological features for this class of systems. This latter contribution paves the way to the generation of synthetic and realistic gas grids with statistically correct network topologies.

LIST OF ACRONYMS

RES	Renewable Energy Sources
HP	High Pressure
MP	Medium Pressure
LP	Low Pressure
MNA	Modified Nodal Analysis

2 Case studies and their graph-based representations

Gas networks aim at transporting (mostly) natural gas from supply up to final consumption physical points. The gas transportation is performed at decreasing levels of pressure, which typically range from ~ 10^1 bar (in high pressure, transmission pipelines) down to ~ 10^{-2} bar (in low pressure, final distribution pipelines). By way of example, in Italy high pressure (HP) networks operate at pressures higher than 5 bar; networks whose pressures are comprised between 0.04 and 5 bar belong to the medium pressure (MP) class; the definition of low pressure (LP) networks applies instead to all the pipes that work at a lower pressure than 0.04 bar [13]. For sake of clarity, we point out that all the pressure levels specified in the paper refer to gauge pressures.

At a transmission level (high pressures), the gas is displaced my means of compressor stations which compensate for the pressure drops occurring along the pipelines. On a distribution level (medium and low pressure), the motion of the gas is induced by cascading pressure drops occurring in correspondence of pressure reduction stations. In this sense, pressure reduction stations constitute the interface between different levels of pressure and, consequently, they can represent either injection or consumption points of the network, depending on the boundaries of the analysis.

Three case studies of real gas networks are described in the present section. All of them are analyzed and compared from a topological perspective to identify relevant features of their network structure. One of the three case studies is therefore exploited for testing and validating our modelling and simulation approach (see Section 4), thanks to the availability of reference operational data.

2.1. Description of the case studies

In the present work we use topological and operational information of real gas networks provided by the network operators of three municipalities - two Italian, one Danish - of small and medium size (with populations ranging from 7,000 to 250,000 inhabitants). All the case studies are passive distribution networks (with no compressor stations) of medium to low pressure.

Network 1 refers to the medium pressure gas distribution system of a city of about 250,000 inhabitants. The network is characterized by one single feeder at 5 bar (at the outlet of a HP/MP reduction station) and no internal pressure reduction stations. Consequently, the gas distribution in Network 1 occurs at one single pressure level and the consumption spots have to be intended as either MP-LP reduction stations supplying lower grid layers or industrial users requiring a MP supply.

Network 2 represents the MP and LP gas distribution infrastructure for a small town of about 7,000 inhabitants. Conversely to the previous case study, Network 2 is characterized by three levels of pressure: a first layer of the network is operated at 5 bar and is directly fed by one single HP/MP reduction station; the lower layers of the networks are instead operated at around 0.5 bar (MP) and 0.02 bar (LP) respectively, and fed by a set of internal pressure reduction stations.

Network 3 constitutes part of the distribution infrastructure for a municipality of around 70,000 inhabitants. The network is operated at two pressure levels (4 bar and 0.1 bar) whose interface occurs in correspondence of a set of internal pressure reduction stations. Conversely to the two previous case studies, Network 3 exhibits two supply points, located at the outlet of two distinct HP/MP pressure reduction stations.

Tab. 1 reports the available information for the three studied gas networks. The topology, in terms of location and existing links between pipelines and reduction stations, is known for all the networks. Conversely, the location of the demand points in the network is known only for the case of Network 1, as well as other operational information such as the instantaneous gas demand of each node and the gas flow rate in pipelines.

TABLE 1 Technical, topological and operational information available for the three case studies.

Available information	Network 1	Network 2	Network 3
Pipelines	✓	✓	✓
Reduction stations	✓	✓	✓
Supply nodes	✓	✓	✓
Demand nodes	✓	×	×
Gas demand at nodes	✓	×	×
Gas flow rates in pipes	✓	×	×
Nodal pressures	×	×	×

2.2. Graph-based representation of gas networks

Similarly to power grids and many other network systems, gas networks are represented with a graph-based abstraction in which edges and nodes act as infrastructure components. At a modelling stage (better described in Section 3 of this work) pipelines, pressure reduction stations and compressor stations are represented as edges of a graph. Gas injection and consumption points and junctions between the pipelines are instead represented by the vertices of the graph. This convention is adopted in the present work consistently with many other contributions in the literature, among which [14,15]. The graph representations of the case studies of Network 2 and Network 3 are reported in Fig. 1.

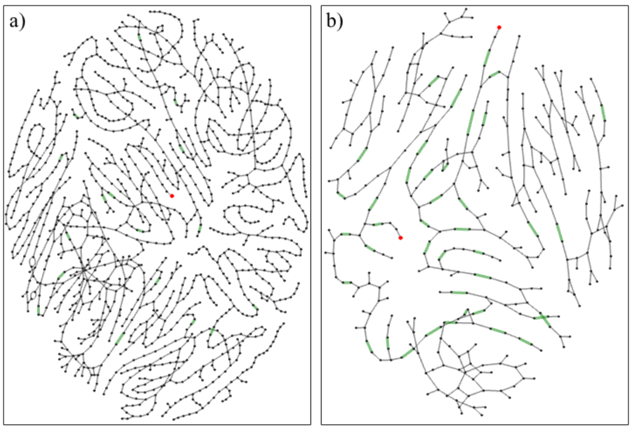

Fig. 1 Equivalent graphs of a) Network 2 and b) Network 3: vertices in red represent gas injection points; edges in green represent pressure reduction stations.

Graph-based representations of energy networks turn out to be effective tools to analyze infrastructures from a topological perspective. Several works proposed topological models to describe the structure of real network infrastructures. Among these contributions, distinguished examples include Barabási-Albert scale-free networks [16], Edrös-Rényi random graphs [17] and Watts-Strogatz small world networks [18]. Topology of network infrastructures has also been extensively deployed to assess the reliability and robustness of networks [15,19,20] and to build synthetic network models for reproducing random case studies with realistic structural properties [21–23]. As a contribution toward the generation of virtually illimited realistic cases studies of multi-energy systems involving gas networks, we extract and compare specific topological metrics for the three real gas grids described in the previous section. The metrics are illustrated in Table 2.

TABLE 2 Topological metrics extracted from the three gas networks.

Metrics	Network 1	Network 2	Network 3
Number of vertices	1274	1238	373
Number of edges	1291	1271	384
Fundamental cycles	18	34	12
Av. Degree	2.03	2.05	2.06
Global Clustering Coeff.	0	0	4.5E-03
Average Path Length	63.3	55.2	29.2

Network 1 and Network 2 feature comparable sizes, whereas the number of nodes in Network 3 is noticeably lower. All the networks exhibit average node degree values close to 2, due to the diffuse presence of linear paths of pipelines and reduction stations. It is straightforward to notice that, in the case of Network 1, the number of cycles normalized to the number of vertices (or edges) is considerably lower than in the other case studies. In other words, Network 1 features an overall lower cyclicity. The reason behind this difference may rely in the intrinsically different typology of the networks: as a urban MP infrastructure, Network 1 operates at a single pressure level of 5 bar and distributes gas to urban MP/BP reduction stations and industrial users; conversely, the other networks operate down to pressure levels of 0.1-0.02 bar, delivering gas to low-pressure users.

All the case studies exhibit close to zero (or null) global clustering coefficient, which indicates that the density of ties in such networks is considerably low. Additionally, observations on the three network samples suggest that the average path length of gas distribution networks scales with $N/\log(N)^{1.5}$. Consequently, previous topological models of real networks, like Barabási-Albert scale-free networks and Erdös-Rényi random graphs appear to be barely applicable to this category of real-world network systems and additional efforts in developing new algorithms and tools for synthetic network generation are desirable.

3 Modelling and simulation strategy

At a modelling stage, the simplest and most effective approach for the simulation of a possibly complex (i.e., large) gas network is followed, where a circuit-inspired analogy is adopted [24]. In addition, steady-state operation and isothermal assumption are considered, leading to simplified nonlinear dynamical power flow governing equations.

In the electrical analogy, pressure and flow rate are interpreted as the companion voltage and current electrical variables, respectively.

The basic building blocks as the pipelines, compressors and reduction stations are described as two port nonlinear resistive elements as shown in Fig. 2. Additional details on the description of the governing equations for each of the above building blocks are collected in the Appendix.

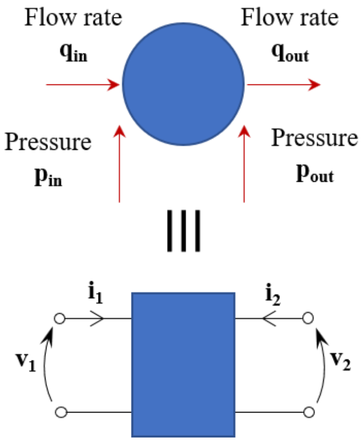

Fig. 2 Building block for pipeline elements of the model.

Based on the above assumptions, pipelines turn out to be defined as voltage controlled current sources governed by the following constitutive relation.

$$i_1 = -i_2 = G(v_1, v_2) \cdot (v_1 - v_2) \quad (1)$$

where $G(v_1,v_2)$ plays the role of a nonlinear conductance, expressed in function of voltages (pressures) through parameters which depend on the geometry of the pipelines and on the fluid-dynamic properties of the gas flow.

Similarly, the equations describing the other two basic blocks, i.e. the compressor and pressure reduction stations, can be readily implemented as two port elements as well, with suitably controlled sources. The related equations are given by (2) and (3), respectively.

$$\begin{array}{ll} i_1 = -i_2 = i & (2.1) \\ \hat{e} = v_2 - v_1 = g(i) & (2.2) \end{array} \quad (2)$$

$$\begin{array}{ll} i_1 = -i_2 = i & (3.1) \\ v_1 - v_2 = E & (3.2) \end{array} \quad (3)$$

The simulation of the gas network is carried out through the classical modified nodal analysis (MNA) tool for circuit analysis, via a custom MATLAB implementation [25].

For the case of a linear circuit, MNA produces the following matrix relation:

$$\mathbf{M} \cdot \boldsymbol{w} = \boldsymbol{a} \quad (4)$$

Where:

- $\boldsymbol{w} \in \mathbb{R}^{\boldsymbol{N}\times\mathbf{1}}$ collects the N unknown variables, represented by $(n - 1)$ voltages of each node excluding a reference node, and the k currents flowing through voltage generators such as the ones with constitutive equations (2.2) and (3.2);
- $\mathbf{M} \in \mathbb{R}^{\boldsymbol{N}\times\boldsymbol{N}}$ includes the parameters defining the characteristics of the circuit elements, together with zeros and ones accounting for the constitutive equations of the voltage sources;
- $\boldsymbol{a} \in \mathbb{R}^{\boldsymbol{N}\times\mathbf{1}}$ contains the values of the known currents driven by the current sources and the values of the independent voltage sources.

In its application to the presented model, equation (4) is built consistently with the relations of equations (1), (2) and (3). It is important to point out that the above matrix equation can be readily generated by inspection, from the information on network topology and the characteristic of circuit elements.

Nevertheless, gas network systems can barely be described by linear models. Underlying fluid-dynamic equations and characteristic curves of technical devices (e.g. gas compressors) require developing nonlinear system representations. Keeping the convention of the circuital analogy, nonlinearities are found in the voltage-controlled current sources described by equation (1) and in the two-port element defined by equations (2), where $g(i)$ is typically nonlinear (see Appendix).

In turn, equation (4) modifies as

$$\mathbf{M}(\boldsymbol{w}) \cdot \boldsymbol{w} = \boldsymbol{a} \quad (5)$$

and numerical techniques are used for the solution. In this work, the classical Newton-Raphson method is iteratively deployed until convergence.

4 Simulation results and validation

The model has been tested on the case study of Network 1, thanks to the availability of the operational data reported in Table 1.

The simulation has been conducted over steady-state conditions characterized by a pressure of 5.0 bar at the outlet of the single feeder of the network, and an overall gas demand amounting to 3.226 Nm^3/s.

The results of the simulation are displayed in Fig. 3, where the size of each vertex of the graph is proportional to the quantity of gas consumed (or injected, in the case of the feeder) by the respective node. Similarly, the width of the edges increases with the gas flow rate streaming within the corresponding pipes. The point of injection is found in correspondence of the large node at 5 bar ($5 \cdot 10^5$ Pa) displayed in yellow.

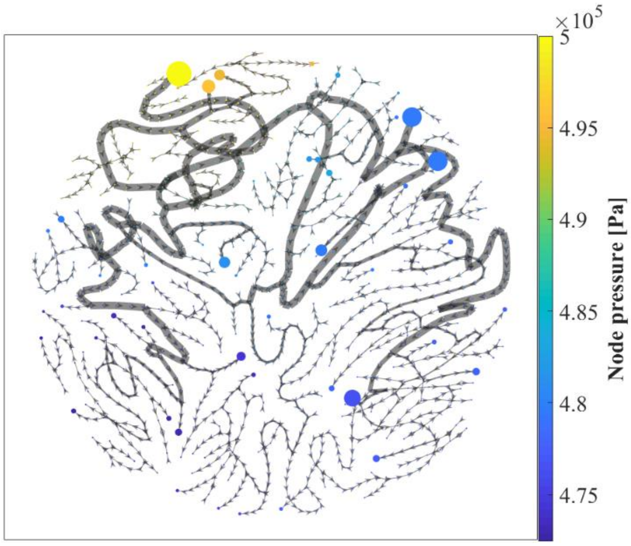

Fig. 3 Visualization of results of the test simulation carried out on Network 1. The size of the network nodes varies with the gas flow rate consumed (or injected) by the node. The thickness of the edges increases with the quantity of gas flowing in the corresponding pipelines. Arrows indicate the direction of the flow in each edge.

At a validation stage, the results have been compared with operational data simulated by the network operator through a commercial software (no information about the software was provided). Due to limited data availability, the validation has been performed on the basis of the only gas flow rates in pipelines. Results show an overall good degree of accuracy of the solution. Simulated gas flow rates exhibit an average relative error of 4.1%; over a total of 1291 pipelines in the network, a set of 14 branches disposed in a row exhibit major errors ranging from 52.4% to 198.5%, meaning that in a few pipelines the simulated flows have opposite direction with respect to the reference data. The remaining pipes of the network, conversely, exhibit an average error value of 2.6%, with peak errors up to 7.9%.

At this validation stage, we would hardly expect a higher agreement between the two datasets. In fact, the comparison has been performed without having access to some significant inputs and properties of the model adopted by the commercial software. Among this lacking information, we list the natural gas composition, the roughness of the pipes and the nature of the model (isothermal or non-isothermal).

In a second stage of validation, the model has been tested and compared with case studies taken from the literature. The target test case is a single 122-km-long pipeline operated at high pressure (84 bar), in conformity with the work by Osiadacz and Chaczykowski [26] and, at this further validation stage, the comparison is performed on the pressure profiles along the pipeline. Our isothermal model is compared with the isothermal model proposed in reference [26]. Overall, the pressure profiles obtained by the two models are very similar, with maximum errors of 1.7% occurring along the pipeline. These minor variations with respect to the reference isothermal are in part due to differences in some model inputs, such as the natural gas composition, which are not specified in the original paper.

Keeping the same test case (122 km long pipeline), we investigated the agreement of our isothermal model with an in-house developed non-isothermal model, extensively described in the work by Pellegrino, Lanzini and Leone [7] (see Fig. 4).

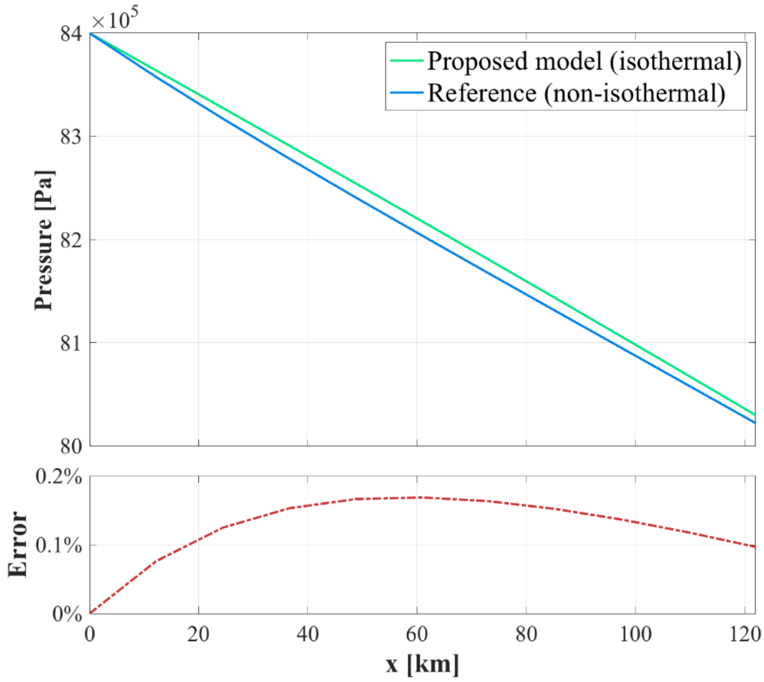

Fig. 4 Comparison of this work's model with the non-isothermal model by Pellegrino et al. [7].

Pressure values obtained with our isothermal model exhibit a high agreement with the non-isothermal reference, evidencing that the assumptions behind our simplified tool do not substantially affect its accuracy. Errors observed against the isothermal model were lower than 0.2% all along the pipeline length (see Fig. 4).

The previous assessment highlighted a good accuracy of simplified models and the feasibility of the proposed modelling and simulation approach for system level integrated multi energy applications.

5 Conclusions

In the present work we described and applied a simulation approach for steady-state applications in gas networks, based on an isothermal assumption. Our gas network model, readily represented be means of a circuital analogy and solved with classical MNA, has showed to guarantee accurate results with respect to other analogous simulation tools while maintaining a simplified physical description. The model validation has been carried out against a commercial tool and another reference from the literature. Furthermore, a comparison with a non-isothermal model allowed to support the validity of our isothermal assumption, and resulting differences of pressure values were lower than 0.2%.

Three case studies of gas networks have been extensively described in terms of structural and topological characteristics and compared to existing network topological models. We provide fresh evidence on the unsuitability of standard models (scale-free networks, random graphs, …) for representing gas network structures and proposed new metrics to be taken as a reference.

Future works will address the generation of synthetic case studies of gas networks, based on the discovered topological features. Electricity and gas network co-simulations will be fully enabled by the availability of these synthetic models. The enhancement of the fluid-dynamic model to a transient version capable of handling the distributed injection of alternative fuels (e.g. hydrogen) is also another aspect to be furtherly addressed.

APPENDIX. Governing equations of the gas network components

Pipelines

The constitutive equation of pipeline elements of the gas network, equation (1), is derived from the momentum conservation law. For the case of a pipeline and assuming stationary and isothermal conditions, the equation can be written as follows:

$$\frac{dp}{dx} + \frac{f}{2D_P}\frac{\dot{m}_P|\dot{m}_P|}{\rho A_P^2} = 0 \qquad \text{(A.1)}$$

where:

- p is the gas pressure;
- x is the longitudinal coordinate along the duct;
- f is the Darcy friction factor, computed using the Colebrook-White relation in function of the gas velocity and viscosity and pipeline's diameter and roughness [27];
- D_P is the diameter of the pipeline;
- $\dot{m}_P$ is the mass flow rate of gas;
- ρ is the density of the gas;
- A_P is the section area of the pipeline.

The real gas virial equation of state is used to establish relations between thermodynamic properties.

$$Z = \frac{p}{\rho R_0 T} \qquad \text{(A.2)}$$

Where R_0 is the specific gas constant, T is temperature of the gas and Z is its compressibility factor, computed as follows:

$$Z = 1 + Bp + Cp^2 + \ldots \qquad \text{(A.3)}$$

B and C are called the second, third, …, n-th virial coefficient and are evaluated according to the SGERG-88 method in function of the natural gas temperature, composition and heating value [28].

Using (A.2) in (A.1) allows building a new integral form (A.4) of the momentum conservation equation, which in turn is used to express the gas flow rate in function of the pressure drop occurring across the endpoints of the pipeline (A.5).

$$\dot{m}_P|\dot{m}_P| = -\frac{D_P A_P^2}{Z R_0 T f L}(p_{out}^2 - p_{in}^2) \qquad \text{(A.4)}$$

$$\dot{m}_P = Y_P \cdot (p_{in} - p_{out}) \qquad \text{(A.5)}$$

In the above equations L is the length of the pipeline, while p_{in} and p_{out} represent the gas pressure at the inlet and outlet of the pipeline, respectively. Y_P plays the role of a nonlinear pseudo-conductance with expression given by (A.6). In the circuital representation described in Section 3, Y_P is the analogous of the nonlinear conductance G of equation (1).

$$Y_P(p_1, p_2) = A_P \frac{(p_1 + p_2)^{0.5}}{|p_1 - p_2|^{0.5}} \cdot \left[\frac{D_P}{Z R_0 T f L}\right]^{0.5} \qquad \text{(A.6)}$$

Pressure reduction stations

Pressure reduction stations are described through a simplified model exerting a constraint over the pressure at the component's outlet. Due to isothermal assumption, changes in temperature driven by the gas expansion are neglected. The constitutive equation for a pressure reduction station is the following:

$$p_{out} - p_R = 0 \qquad \text{(A.7)}$$

Where p_{out} is the pressure at the station's outlet and p_R is a known pressure value representing the constrained regulation pressure.

Compressor stations

A simplified model of compressor stations is implemented. In order to moderate the complexity of the formulation, compressors are assumed to operate at a fixed speed. Under this assumption, the compressor map reduces to a relation between the mass flow rate of the gas and the pressure increase. This relation is approximated with a second-order polynomial equation (A.8).

$$p_{out} - p_{in} = k_0 + k_1 \dot{m}_c + k_2 \dot{m}_c{}^2 \qquad \text{(A.8)}$$

Where p_{out} and p_{in} are the pressures at the outlet and inlet, respectively, while $\dot{m}_c$ represents the mass flow rate flowing in the compressor station. In the equation, k_0, k_1, and k_2 are constant.

Acknowledgements

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