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Dynamic quality tracking of natural gas and hydrogen mixture in a portion of natural gas grid

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Abstract

Direct injection of alternative fuels (biomethane, hydrogen) in the natural gas grid appears to be a promising solution to reach environmental objectives of CO_2 emission reduction in the current energy scenario. This approach is justified by the large amount of biogas producible, which can be upgraded to biomethane; while another proposed solution to increase renewable energy sources exploitation lies in producing hydrogen from excess wind energy, followed by injection in the natural gas grid. Nevertheless, compliance with composition limits and quality constraints in the resulting natural gas mixture has to be analysed in both stationary and dynamic operations, tracking the gas quality downstream the injection point of the alternative fuels. A model was developed to simulate unsteady operation of a portion of gas grid dealing with realistic industrial and residential consumptions concentrated in offtake points. Two case studies were investigated focusing on the comparison between different amounts of hydrogen injection in the pure natural gas flow, yielding composition, flow rate and pressure profiles. The analysis shows how imposed quality thresholds can be respected, although the hydrogen fraction within the natural gas mixture is highly sensitive to the profile and size of the loads connected to the gas pipeline.

Keywords: gas pipeline; dynamic modeling; quality tracking; hydrogen injection;

1. Introduction

In the current energy scenario, an increasing share of renewables is expected, with respect to both fuels and electricity production [1]. Biogas production can contribute significantly to CO_2 emission reduction objectives and the injection in the natural gas infrastructure, after an upgrading process (biomethane), is one of the most suitable pathways for enhancing biogas use [2]. On the other hand, increasingly high share of wind and solar power causes issues on the electricity transmission grid due to capacity limits and

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increases balancing requirements for grid control. Among several solutions, the chemical energy storage by means of hydrogen production seems a promising solution to handle large amounts of energy (MWh to GWh scale); one option frequently addressed in literature is the direct injection of the produced hydrogen in the natural gas grid according to the ‘power-to-gas’ concept [3].

According to this picture, in the near future the natural gas grid could start receiving many injections of different gases; due to their different properties (heating value, density), the operation of the network itself, the gas quality and the energy delivered to customers can be significantly influenced. Nowadays, first evidences of such problems are caused by the growing diversification of natural gas sources allowed by LNG transport in many markets. Therefore, quality tracking in complex gas transport infrastructure is an increasingly urgent need.

Several models are currently available in the open literature aiming both at stationary and dynamic description of gas pipelines; nevertheless, they usually assume a fixed composition of the gas mixture. While in the past this approach was in line with the usual operating conditions of transport and distribution networks, nowadays the influence of composition becomes significant. Different approaches to balance equations solving are possible, i.e. [4–8].

In this work, a dynamic model of gas transportation in a pipeline considering gas composition is described and then applied to a case study.

Nomenclature

ρ	Gas density [kg/m^3]
$\hat{\mathcal{R}}$	Specific gas constant [J/kg K]
S	Pipe section [m^2]
D	Pipe diameter [m]
f	Friction factor [-]
HHV	Higher heating value [MJ/Sm^3]
NG	Natural gas
k	Pipe roughness [m]
p	Pressure [Pa]
q	Mass flow [kg/s]
Re	Reynolds number [-]
t	Time [s]
v	Gas velocity [m/s]
WI	Wobbe index [MJ/Sm^3]
x	Spatial coordinate [m]
z	Compressibility factor [-]

2. Dynamic model of pipeline

In order to track the composition of a gas through a pipeline, the system fluid dynamic balances have to be solved according to the gas variable thermo-physical properties. Equations (1) and (2) describe one-dimensional mass and momentum balances for a pipeline; due to the compressibility of the fluid, also the equation of state for real gases has to be included in the model (Eq. (3)).

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho v)}{\partial x} = 0 \tag{1}$$

$$\frac{\partial(\rho v)}{\partial t} + \frac{\partial(\rho v^2)}{\partial x} + \frac{\partial p}{\partial x} \pm f \rho \frac{v^2}{2D} = 0 \tag{2}$$

$$p = \rho z \hat{\mathcal{R}} T \tag{3}$$

The resulting PDE equations are than discretized in space, according to the approach reported in [6], yielding to the system of ODE that is solved by the model (Eq. (4)),

$$\begin{cases} \dfrac{\partial p}{\partial t} = -\alpha \cdot \Delta q \\ \dfrac{\partial q}{\partial t} = -\alpha \cdot \dfrac{2q}{p} \Delta q + \left(\alpha \dfrac{q^2}{p^2} - \beta \right) \cdot \Delta p - \gamma \dfrac{q^2}{p} \end{cases} \tag{4}$$
$$\alpha = \frac{z\hat{\mathcal{R}}T}{S \cdot \Delta x} \quad \beta = \frac{S}{\Delta x} \quad \gamma = f \frac{z\hat{\mathcal{R}}T}{2S \cdot D}$$

where the independent variables are the pressure p and the mass flow q, while the coefficients are functions of the local thermo-physical properties. Several correlations are available to calculate both friction factor f and compressibility factor z depending on composition, pressure and temperature; here we assume the Hofer approximation of Colebrook-White formula (Eq. (5)) [4]:

$$f = \left[2 \log_{10} \left(\frac{4.518}{Re} \log_{10} \frac{Re}{7} + \frac{k}{3.71\, D} \right) \right]^{-2} \tag{5}$$

and the Papay correlation (Eq. (6)) [4]:

$$z = 1 - 3.52\, p_r\, e^{-2.260\, T_r} + 0.274\, p_r^2 e^{-1.87\, T_r} \tag{6}$$

where p_r and T_r are the pseudo-critical reduced pressure and temperature of the mixture. Given the appropriate initial and boundary conditions, the system is solved by the stiff ODE solver functions (*ode15s*, *ode23s* or *ode23b*) of MATLAB®.

The quality is tracked updating the composition in each volume of the discretization during the integration time step. A mass balance equation is implemented for each species, considering the flow inside the pipeline, external injection and customers offtakes. The approximation given by the hypothesis of perfect mixing within each volume is low, compared to the operating conditions of the system. Thermo-physical properties are updated according to the evolution of the composition.

3. Hydrogen injection case study

The model is applied to the case of hydrogen injection in a real NG pipeline to evaluate the effects on delivered energy and gas quality. Given the flow profiles as boundary conditions, two days of operation are simulated, monitoring the heating value and the composition in significant points of the pipeline.

As a case study, we consider the injection in a medium pressure (50 bar, 24" diameter) pipeline; the total length of the pipe is 50 km (Fig. 1a).

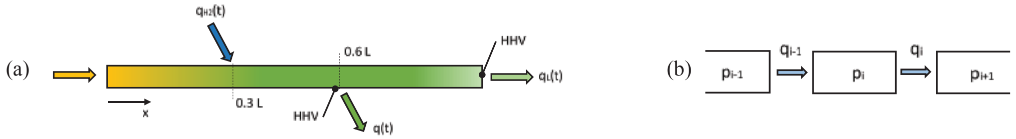


Fig. 1 - (a) Conceptual scheme of the simulated pipeline (b) Applied discretization scheme.

The system described by Eq. (4) is solved considering the discretization in Fig. 1b and the boundary conditions in Fig. 1a. Inlet pressure is fixed, assuming that there is a control system upstream (compression station or pressure-reducing valve), while mass flow is imposed at outlet. The system includes an injection of hydrogen at 0.3×L and an extraction point at 0.6×L, feeding a group of NG customers. Assumptions on mass flow profiles are detailed in next section.

3.1. Injections and load profiles

Pipeline reference flow (q_L) and injected hydrogen flow (q_{H2}) profiles are shown in Fig. 2a. The first one is a flow profile measured in a similar pipeline located in South Italy on a spring day. Hydrogen flow is calculated respecting the most restrictive limit on hydrogen volumetric fraction (max 5%vol), HHV (34.95÷45.28 MJ/Sm3) or WI (47.31÷52.33 MJ/Sm3) (see Fig. 2b; heating value and Wobbe index limitations reflect typical Italian and European NG grid codes) as they result from the simulation of the production of a P2G system connected to a wind farm carried out in a previous work [9]. Hydrogen production is therefore subjected to fluctuations of the intermittent energy source; a buffer storage smooths the injection profile, but hydrogen flow depends on excess wind availability (for instance, in the last hours of the considered period, the production is zero). The reference composition of natural gas considers a Russian gas (96.67% CH_4, 1.67% C_2H_6, 0.62% C_3H_8, 0.26% CO_2 and, 0.79% N_2, HHV 38.09 MJ/Sm^3).

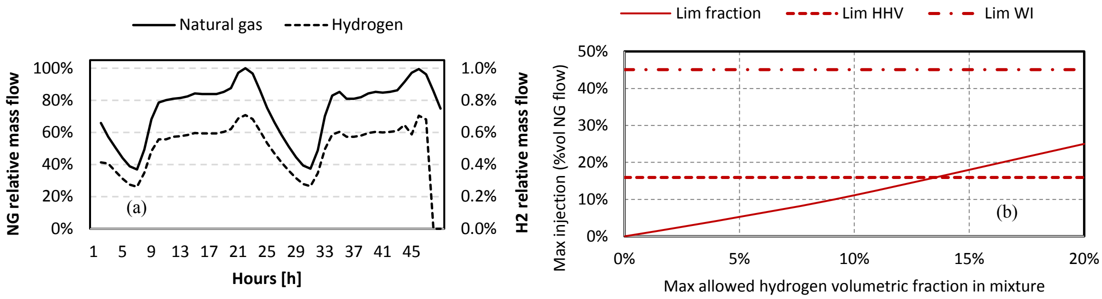


Fig. 2 - (a) Natural gas flow and hydrogen injection in a medium pressure pipeline (reference NG flow: 42.2 kg/s, 215 kSm^3/h) (b) Limits on hydrogen injection due to composition, HHV or WI.

Assumptions about load consumption profiles are shown in Fig. 3. A 'residential' profile (including domestic loads and small firms of a nearby city) repeats itself in the two days, while an industrial profile is included in the first day, corresponding to a power plant (400 MW_{el} natural gas combined cycle) whose output decreases close to noon due to PV plants contribution to electricity production; the power plant is then kept out of operation in the second day.

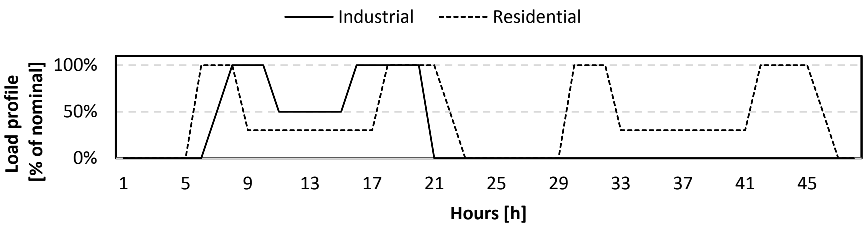
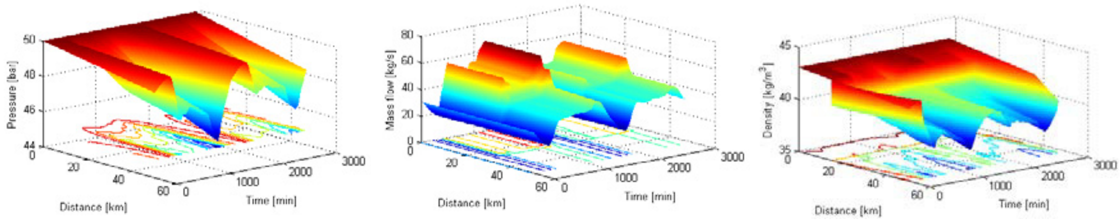


Fig. 3 - Load profiles (nominal flow rates: 12 kg/s).

3.2. Fluid-dynamics

Some considerations can be done with respect to the influence of composition on gas density and pressure drops. Pressure drop (Fig. 4a) varies in time due to gas properties influence and, mostly, due to flow variations. Mass flow is shown in Fig. 4b, where the presence of the strong industrial gas offtake is evident during the first day of operation; flow peaks are lower in the second day of operation because of the presence of the residential demand alone. Flow profile at the outlet of the pipe is imposed and varies in time according to the conditions of the downstream network (see Fig. 2a).



(a) (b) (c)

Fig. 4 - (a) Pressure profile (b) Mass flow profile (c) Density profile as function of spatial and time coordinates.

The most interesting property profile is related to the density (Fig. 4c), where two contributions are overlying. A first effect is due to pressure drop that generates fluctuations at the outlet. From the point of view of this work, it can be evidenced the density step at about one-third of the pipe length; hydrogen has a much lower density than natural gas at given pressure and temperature, thus even the effect of a small injected amount becomes evident. Density has a strong influence on delivered energy, too: hydrogen has a high heating value on mass basis, while a low one on volumetric basis; therefore, a strong reduction on density requires a higher volumetric flow in order to deliver a constant amount of energy.

3.3. Gas composition and delivered energy

Hydrogen molar fraction profiles at the bleeding point and at the outlet of the pipeline are shown in Fig. 5, in comparison with the profile of injected hydrogen.

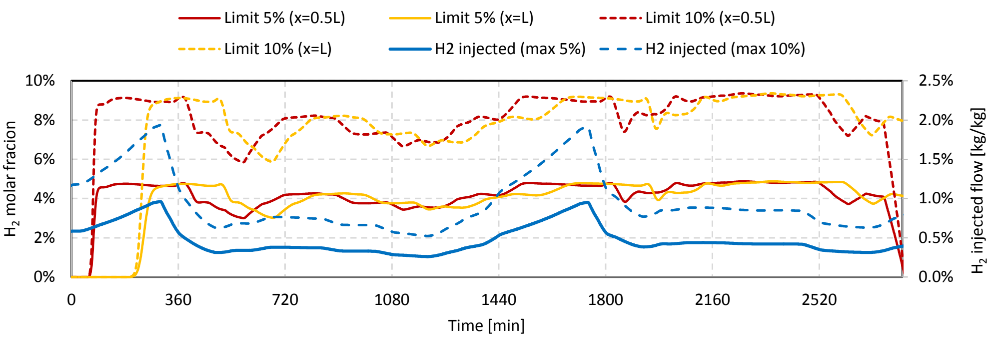


Fig. 5 - Hydrogen volumetric fraction profile and injected hydrogen flow (relative to natural gas flow in pipeline on mass basis).

Gas velocity causes a time shift between the profiles in different spatial points (i.e. at middle length and at outlet), but the shape remains essentially unvaried. Variations in the injected hydrogen profile have no direct correspondence on the hydrogen fraction in the mixture, mainly due to the low amount of hydrogen with respect to the natural gas flowing in the pipe. As it can be observed, the most sensible fluctuations in hydrogen fraction correspond to large offtakes (i.e. industrial in the first day); as the hydrogen flow is calculated from the reference flow (assigned at the outlet), the presence of an amplified flow due to extraction causes a dilution of the gas in the mixture. On the other hand, a sudden vanishing of a load with consequent reduction of the overall gas flow rate which has to be transported in the pipeline can lead to peaks in hydrogen concentration, possibly up to crossing the quality thresholds if the injection is not modulated in real time. A less restrictive limit on max admitted hydrogen fraction (i.e. $10\%_{vol}$) yields magnified profiles, but essentially with the same behavior.

Fig. 6 compares the volumetric HHV of the H_2-NG mixture to the one of pure NG. The reduction due to hydrogen injection is evident and the general behavior reflects the hydrogen concentration profiles discussed above. Gas flow simulation also allows an estimation of the delay in heating value steps experimented along the pipeline, given its operation parameters and the injection profiles.

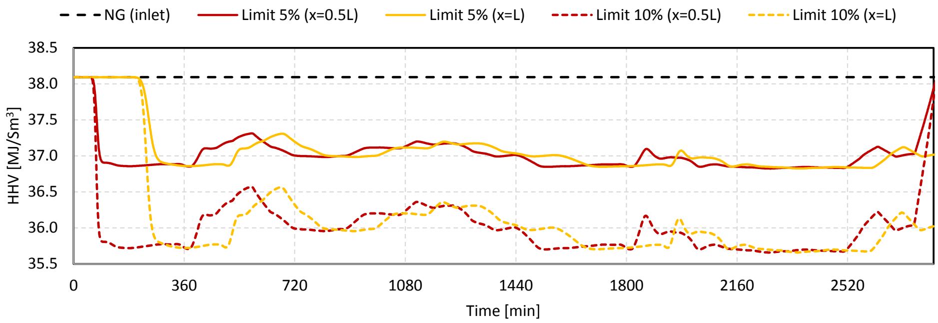


Fig. 6 - HHV profile at pipeline half-length (red) and exit (yellow) depending on max admitted H_2 fraction at injection.

4. Conclusions

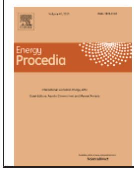
Operation of natural gas grid requires an accurate knowledge of the quality of the natural gas delivered to customers downstream possible injection points of alternative gases. A tool was developed in order to simulate pressure and composition time profiles in a pipeline subjected to intermediate injections of different gases. The model, applied to the case study of hydrogen injection in a medium pressure pipeline, shows dynamic effects in hydrogen concentrations and heating values caused by unsteady operation of the grid; the influence on customers' devices and appliances can be significant, justifying the effort in dynamic modeling of gas composition.

Further work will address the quality tracking in a more complex meshed network, considering the transported and delivered energy as relevant parameter, aiming to further improve the description of real gas transport infrastructures under the new operating regime caused by alternative fuels injection.

References

[1] IEA (International Energy Agency), "ETP - Energy Technology Perspectives 2012." OECD/IEA, 2012, p. 690.
[2] IEA (International Energy Agency), "Technology Roadmap - Bioenergy for Heat and Power." OECD/IEA, 2012, p. 68.
[3] M. Lehner, R. Tichler, H. Steinmueller, et al., "Power-to-Gas: Technology and Business Models." Springer, 2014, p. 93.
[4] M. Schmidt, M. C. Steinbach, and B. M. Willert, "High detail stationary optimization models for gas networks," *Optim. Eng.*, Mar. 2014.
[5] A. Herrán-González, J. M. De La Cruz, B. De Andrés-Toro, et al., "Modeling and simulation of a gas distribution pipeline network," *Appl. Math. Model.*, vol. 33, no. 3, pp. 1584–1600, Mar. 2009.
[6] H. Aalto, "Transfer Functions for Natural Gas Pipeline Systems," in *Proceedings of the IFAC 17th World Congress*, Jun. 2008.

[7] A. Osiadacz and M. Chaczykowski, “Comparison of isothermal and non-isothermal pipeline gas flow models,” *Chem. Eng. J.*, vol. 81, no. June 2000, pp. 41–51, 2001.
[8] D. Matko, G. Geiger, and W. Gregoritza, “Pipeline simulation techniques,” *Math. Comput. Simul.*, vol. 52, no. 3–4, pp. 211–230, Jun. 2000.
[9] G. Guandalini and S. Campanari, “Wind power plant and power-to-gas ystme coupled with natural gas grid infrastructure: techno-economic optimization of operation [accepted],” GT2015-42229, in *Proceedings of ASME Turbo Expo 2015*, Montreal, Canada, Jun. 2015.



Biography

Giulio Guandalini is a PhD student at Politecnico di Milano. His thesis work aims at assessment of “power-to-gas” systems from a technical and economical point of view. His expertise is in the field of complex energy systems simulation.