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Dynamic modeling of natural gas quality within transport pipelines in presence of hydrogen injections

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HIGHLIGHTS

- Alternative energy-based approach for natural gas grid modeling.
- Dynamic modeling of pressure and flows according to customer requirements.
- Local composition calculation and gas quality tracking performed.
- Analysis of delivered gas properties after hydrogen injection in a single pipe (case study).

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ABSTRACT

In the near future, the natural gas grid could face an increasing share of alternative fuels (biomethane, hydrogen) injected in addition to the traditional mixture. Indeed, this pathway is particularly promising in order to reach environmental objectives of CO_2 emissions reduction, in both thermal and electrical final uses. Biogas is already abundantly produced and could be easily upgraded to biomethane; hydrogen technologies are still under development, but they can help the exploitation of the increasing availability of renewable energy sources. A promising solution to problems due to unpredictable fluctuations of renewable energy production (in particular related to wind parks) or excess energy with respect to the load lies in hydrogen production by electrolysis and further injection in the natural gas grid. In this scenario, the effects on design and management of the transport infrastructure should be investigated, and the compliance with composition limits and quality constraints has to be analyzed in both stationary and dynamic operation, tracking the gas quality downstream the injection point of the alternative fuels. A model was developed to simulate the unsteady operation of a portion of the gas grid; with respect to traditional volume-based approaches, a novel energy-based approach is developed, including variable composition along the pipes and allowing to consider a given energy delivery to customers as a constraint. After the validation against available operational data, a case study considering concentrated realistic domestic and industrial offtakes is simulated. The effects of hydrogen injection, usually not considered in NG grid design and operation analyses, are investigated in terms of composition, flow rate and pressure profiles with comparison to the reference natural gas case. The analysis shows how imposed quality thresholds can be respected, although the effects on calorific value, Wobbe index and density are not negligible; results indicate that the allowed hydrogen fractions are limited and highly sensitive to the profile and size of the offtakes connected to the pipeline. The discussion also evidences the potential impact of hydrogen injection on gas metering and measurements errors.

1. Introduction

In the current energy scenario the share of renewables is expected to increase continuously, with respect to both fuels and electricity, also as a result of progressively stricter environmental policies [1–3] and general concern for emissions reduction. Biogas production can contribute significantly and the injection in the natural gas grid, after the upgrading process (e.g. the production of biomethane), is one of the most suitable pathway for valuing it [4,5]. With respect to traditional use of biogas for local cogeneration, the injection of 'green' gas in the grid improves also the environmental performances of distributed final users (i.e. domestic heating, industrial heat production). The majority of current biogas

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Nomenclature

d	relative density to air (–)
D	pipe diameter (m)
ε	surface roughness (m)
$\dot{E}$	HHV energy flow (MJ/s)
Υ	hydrogen/natural gas flow ratio (–)
g	gravitational acceleration (m/s^2)
h	elevation (m)
HHV	higher heating value (MJ/Sm^3)
λ	friction factor (–)
p	pressure (Pa)
ρ	gas density (kg/m^3)
ρ_0	air density (kg/m^3)
q	mass flow rate (kg/s)
$\tilde{R}$	mass specific gas constant (m^3 Pa/K/kg)
Re	Reynolds number (–)
RMSE	root mean square error (–)
S	pipe cross section (m^2)
t	time (s)
T	temperature (K)
u	gas velocity (m/s)
$\dot{V}$	volumetric gas flow rate (m^3/s)
W	molar mass (kg/kmol)
WI	Wobbe index (MJ/Sm^3)
x	spatial coordinate (m)
$\bar{x}$	molar fraction
z	compressibility factor
LNG	liquefied natural gas
NG	natural gas
ODE	ordinary differential equation
P2G	power-to-gas
PDE	partial differential equation
TSO	transmission system operator

Subscripts

A	absolute
el	electric
mix	mixture (hydrogen/natural gas)
ng	natural gas
R	relative
r	pseudo-critical reduced property

production is utilized for local renewable heat and power generation; in the future, the share of upgraded biogas injected in the grid could reach up to 10–20% of the total demand [6], although the evolution of the market is subject to uncertainties related to energy policy evolution. Objectives set by Germany and Netherlands, which are the two countries with the strongest biogas market in Europe, are to cover 7% and 2% respectively of the total natural gas demand by biomethane in 2020.

Moreover, among the different solutions proposed to deal with the unpredictability of some renewable energy sources (wind and solar), energy storage in chemical form is a suitable option [7]. In particular, hydrogen production by means of electrolysis (the so-called power-to-gas or P2G concept) seems a feasible solution in order to reduce issues due to capacity limits and balancing requirements for electricity transmission grid control in case of high wind and solar power share, as well as a solution to manage very large storage capacities (MW to GW scale) [8]. Although the best economical valorization of hydrogen would come from its direct use in pure form, e.g. for feeding fuel-cell vehicles, hydrogen injection in the natural gas grid is a mid-term solution that avoids the necessity of a strictly contemporaneous and parallel development of final uses for the distributed hydrogen and postpones the development of a dedicated infrastructure [9]. As a term of comparison, considering a current consumption of natural gas of about 80 billons Nm^3 per year (Italy, Germany, UK [10]), a fraction of 5%$_{vol}$ of hydrogen in the natural gas grid infrastructure could potentially store about 20 TW h per year of electrical energy from renewables, i.e. around 60–70% of the yearly production from wind and solar (Italy, [11]).

According to this picture, the management of the natural gas grid infrastructure will experience strong changes in the next future. In particular, the traditional assumption of limited variations in gas composition, typical of classic NG distribution scenarios, will not be valid anymore; the grid could start receiving several different gases, whose properties variations (heating value, density) could significantly influence the management of the grid. On the other hand, in most countries the regulation authorities are requiring more and more accuracy in the control of the gas quality delivered to the customers. Nowadays, first evidence of such issues are caused by the increasing diversification of gas sources, aiming at strategical safety of supply, which includes both pipeline connections to different production fields and a wider use of regasification of LNG coming from multiple countries. The addition of biomethane injections and, lately, of hydrogen injections will substantially increase the problem complexity. Therefore, the development of quality tracking tools in complex gas transport infrastructures is a urgent need.

Several models were developed in last decades [12], mainly aiming at optimal design of large-scale gas transport infrastructure; recently, an effort in modeling the dynamic behavior of the natural gas grid addressed the issue of pressure fluctuations due to an irregular usage of natural gas-fired power plants in presence of highly variable production from wind [13]. In literature, both stationary and dynamic analytical models are presented, with several dedicated solution methods dealing with the particular structure of the PDEs involved; nevertheless, they usually assume a constant composition of the gas mixture. An improvement is therefore required in order to properly take into account the presence of multiple sources of different kind of natural or synthetic gases. Literature models can be classified according to the solution approach. Key choice is whether or not enter the field of automatic control systems. In the first case, authors aim at extracting basic information about the behavior of the pipeline system – mainly for operation control purposes – by looking at the characteristics of the transfer functions obtained by applying a Laplace transform, after discretization and linearization of the analytical model [14,15]. On the opposite side, numerical solution of the two central PDEs of the model (continuity and momentum conservation equations) is sought with various levels of simplification [16–18]. An additional alternative exploits the electrical analogy, which leads to a less complex set of first-order ODEs [19].

In this work, a dynamic model is proposed that avoids the assumption of constant composition by evaluating the mixing of gas flows within any spatial interval at each time step. Moreover, since the energy content of the new blends of fuel gas delivered to the customers cannot be evaluated in simple terms of consumed volumes (as per the traditional gas metering approach), the model adopts energy-based boundary conditions to respect customers' requirements of a given energy delivery. After the model description, a validation of the approach is performed by means of

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