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Greening the gas network – The need for modelling the distributed injection of alternative fuels

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ABSTRACT

The recent unfolding of natural gas sources, especially unconventional gas shales and substituted natural gas from renewables, can boost the transition toward a low carbon energy system. However, it is necessary to study how the gas network, traditionally supplied with fossil fuel gas, could be operated in a more complex scenario that includes multiple and distributed energy sources.

This work deals with the development of a mathematical model able to simulate transmission pipeline networks under steady-state condition while adopting a non-isothermal approach. A review of modelling approaches of fluid flow in gas pipelines and gas pipeline networks is provided. An algebraic formulation to describe compressible fluid networks is also described in detail and implemented for the first time in this work with the aim to simulate the distributed injection of green fuel gasses into the natural gas network. Hydrogen blending (e.g., from power-to-gas systems) and substituted natural gas (e.g., from biogas upgrading or power-to-gas systems) injection are considered.

A numerical simulation of a regional-scale natural gas transmission system is performed where green gasses are injected into the grid. In the case of hydrogen blending, the maximum quantity of injectable hydrogen in each node is calculated to achieve a 10% blend as an upper constraint. In conclusion, the impact of green fuels injection in the gas network on the resulting natural gas quality (i.e., Wobbe index, gas gravity, higher heating value) is investigated thoroughly.

1. Introduction

Natural gas has been identified as the fuel for the 21st century according to several influential scientists and institutions [1]. It is the fossil fuel with the lowest emission factor (56.1 tCO_2/TJ) and the recent relevant conventionaland unconventional discoveries suggest an increasing role in the global energy system.

The International Energy Agency [1] foresees that natural gas will supply 25% of the 2040 world primary energy demand (this is the new policies scenario of the World Energy Outlook 2014). Nonetheless, unconventional and green gas sources could play a role in the diversification of supply. Smil recently discussed prospects of natural gas in modern societies as a leading fuel for the twenty-first century [2].

The life-cycle environmental impact of unconventional gas is still under much debate [3]. Hydrogen from renewables (power-to-gas) and synthetic natural gas (SNG) from bio-syngas or biogas can green instead the gas network.

Capturing the benefits of multiple and distributed sources network is high valuable from a wide variety of perspectives including high efficiency, environmental, economics, and energy security.

This work is a contribution toward the understanding of the transition of natural gas networks in a low carbon energy system. Recent advances on gas network modelling and simulation are discussed in this work. We also present a case study for hydrogen and SNG injection into an existing regional-scale gas network. A revised gas network mathematical formulation is used to simulate the gas grid thermofluidynamic behavior.

1.1. The case for Substitute Natural Gas (SNG) in future energy networks

SNG can be produced from fossil fuels (e.g., coal), biomass (e.g., phytomass and zoomass, municipal waste) [4,5], biogas upgrade [6,7] and from intermittent renewable electrical energy sources (e.g., wind farm, solar farm) through power-to-gas applications [8,9].

Biogas upgrade to injectable gas is currently one of the most mature option [10]. Incentives to support SNG injection from biogas upgrading pathways are already available in many countries such as United

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Nomenclature

Symbol	Meaning
A	Inside cross sectional area of a pipe.
b	Number of branches.
B	Second virial coefficient.
C	Third virial coefficient.
C_{GAS}	Composition of the gas in each node.
$\mathbf{C_{GAS}}$	Matrix containing the composition of the gas in each node.
c_p	Specific heat at constant pressure.
$c_{p_{ent}}$	Specific heat at constant pressure at the temperature of the gas entering the grid from the external ambient.
$c_{p_{T_C}}$	Specific heat at constant pressure at the maximum temperature admissible after a compression station.
$c_{p_{T_R}}$	Specific heat at constant pressure at the minimum temperature admissible after a regulation station.
D	Pipe inner diameter.
$\mathbf{E}$	Matrix which elements are calculated as reported in (37).
f	Darcy friction factor.
$\mathbf{F}$	Vector which elements are calculated as reported in (38).
g	Gravitational acceleration.
G	Gas mass stream.
$\mathbf{G}$	Vector of mass streams flowing in each branch.
$\mathbf{G_C}$	Vector of mass streams flowing in the compression stations.
$\mathbf{G_{ext}}$	Vector of mass streams entering the nodes
$\mathbf{G_P}$	Vector of mass streams flowing in the pipe.
$\mathbf{G_R}$	Vector of mass streams flowing in the regulation station.
h	Gas specific enthalpy.
$\mathbf{h}$	Vector of the specific enthalpy of the node upstream the branch.
$\mathbf{h_e}$	Vector of the specific enthalpy of the node upstream the branch.
$\mathbf{h_{ent}}$	Vector of the enthalpy of the flow rates entering the nodes from the external ambient.
$\mathbf{H_{ext}}$	Vector of the equivalent power injected or extracted in each node.
HHV	Vector of the Higher Heating Value of the gas injected or extracted in each node.
$\mathbf{h_{u,C}}$	Vector of the specific enthalpy exiting the compression station.
$\mathbf{h_{u,C}}^*$	Vector which elements are calculated as reported in (26).
$\mathbf{h_{u,P}}$	Vector of the specific enthalpy exiting the pipelines.
$\mathbf{h_{u,R}}$	Vector of the specific enthalpy exiting the regulation station.
$\mathbf{h_{u,R}}^*$	Vector which elements are calculated as reported in (29).
IE	Diagonal matrix (n×n) which terms indicates if the mass stream exchanged with the external ambient is entering (−1) or exiting (+1)
k	Heat capacity ratio.
$\mathbf{K}$	Vector which elements are calculated as reported in (20).
k_0	Constant term of the polynomial curves describing compression maps
$\mathbf{k_0}$	Vector containing the constant terms of the polynomial curves describing compression maps.
k_1	One-degree term of the polynomial curves describing compression maps.
$\mathbf{k_1}$	Vector containing the one degree terms of the polynomial curves describing compression maps.
k_2	Two-degree term of the polynomial curves describing compression maps.
$\mathbf{k_2}$	Vector containing the two degree terms of the polynomial curves describing compression maps.
L	Pipeline length.
$\mathbf{L}$	Diagonal matrix containing the specific heat at constant pressure at the inlet section of the branches.
$\mathbf{M}$	Diagonal matrix which elements are calculated for each pipeline as reported in Eq. (22).
MG	Diagonal matrix (b×b) which terms are the mass streams in each branch.
$\mathbf{MG_a}$	Diagonal matrix (b×b) which terms are the absolute values of the mass streams in each branch.
$\mathbf{MG_{ext}}$	Diagonal matrix (n×n) which terms are mass streams exchanged with the external ambient in each node.
$\mathbf{MG_{ext,a}}$	Diagonal matrix (n×n) which terms are the absolute values of the mass streams exchanged with the external ambient in each node.
n	Number of nodes.
$\mathbf{N}$	Vector which elements are calculated as reported in (23).
p	Gas pressure.
$\mathbf{p}$	Vector of gas pressure.
$\tilde{\mathbf{p}}$	Vector of the known pressures.
$\mathbf{p_R}$	Vector of the pressure of the node after the regulation stations.
$\mathbf{Q}$	Vector which elements are calculated as reported in (25).
R	Specific gas constant.
Re	Reynolds number.
$\mathbf{S}$	Vector which elements are calculated as reported in (28).
s	Variable assuming +1, if p_1 is higher than p_2, or −1, if p_2 is higher than p_1.
T	Gas temperature.
$\mathbf{T}$	Vector of gas temperature in the nodes.
T_C	Maximum admissible temperature after a compression station.
$\mathbf{T_{ent}}$	Vector of the temperature of the flow rates entering the nodes from the external ambient.
T_R	Minimum admissible temperature after a regulation station.
T_s	Soil temperature.
u	Gas velocity.
U_L	Linear overall heat transfer coefficient.
$\mathbf{V}$	Matrix which elements are calculated as reported in (34).
$\mathbf{V_{ent}}$	Matrix which elements are calculated as reported in (31).
$\mathbf{W}$	Matrix which elements are calculated as reported in (31).
$\mathbf{W_{ent}}$	Matrix which elements are calculated as reported in (35).
x	Element of the incidence matrix.
$\mathbf{X}$	Incidence matrix.
$\mathbf{X_C}$	Compression stations incidence matrix.
$\mathbf{X_R}$	Regulation stations incidence matrix.
$\mathbf{X_P}$	Pipe incidence matrix.
$\bar{\mathbf{X}}$	Incidence matrix which includes the nodes for which the pressure is known.
Y(p)	Pseudo-conductance of the pipe.
$\mathbf{Y}$	Vector of the pseudo-conductance of the pipes.
Z	Compressibility factor.
α	Pipe slope angle.
β	Coefficient for the calculation of the average gas temperature.
γ	Coefficient for the calculation of the average gas temperature.
$\Delta\mathbf{p}$	Vector of the pressure drop of the pipeline.
ϵ	Roughness height.
η	Isentropic efficiency
μ_{JT}	Joule-Thomson coefficient.
$\mu_{JT_{ent}}$	Joule-Thomson coefficient at the temperature of the gas entering the grid from the external ambient.
$\mu_{JT_{T_C}}$	Joule-Thomson coefficient at the maximum temperature admissible after a compression station.
φ	Convergence weighting factor.
P	Gas density.
χ	Convergence weighting factor.
ψ	Convergence weighting factor.
ω	Convergence weighting factor.