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STEADY-STATE SIMULATION OF GAS DISTRIBUTION NETWORKS IN THE PRESENCE OF LOCALIZED HYDROGEN INJECTIONS

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ABSTRACT

Hydrogen plays a crucial role in the zero-carbon emission objective of the global 2050 long-term strategy. The injection into the gas grid, of the hydrogen "green" gas produced by the power to gas technology, is a potential solution to reduce CO_2 emissions. This paper developed a steady-state model for quality tracking in gas networks. A gas distribution network with two principal natural gas sources and a localized hydrogen source was simulated. Results show how the hydrogen injected affects the pressure and the quality of gas delivered. The influence depends on the location of the injection node and changes during the day. It can be reduced by choosing an appropriate position of the hydrogen source.

Keywords: Natural gas, Alternative gas, Hydrogen injection, Gas quality, Gas distribution network.

NONMENCLATURE

Symbols	
D	Pipe diameter [m]
$\dot{E}$	Energy flow [MJ/s]
g	Gravitational acceleration [m/s^2]
HHV	Higher heating value [MJ/Sm^3]
L	Pipe length [m]
M	Molecular weight [kg/kmol]
$\dot{m}$	Mass flow rate [kg/s]
p	Pressure [Pa]
$\dot{Q}$	Standard volumetric flow rate [Sm^3/h]
R	Gas Constant [J/mol K]
T	Temperature [K]
WI	Wobbe index [MJ/Sm^3]
y	Mass fraction [-]
Z	Compressibility Factor [-]
ε	Surface roughness [m]
θ	Pipe inclination angle [deg]
λ	Friction Factor [-]
ρ	Density [kg/m^3]

1. INTRODUCTION

Global warming is a severe problem for the planet. Immediate and significant actions are essential to arrest irreversible climate change. The 2050 long-term strategy [1], defined by the European Commission, leads towards zero greenhouse gas emission by 2050. In this context, a feasible pathway is to store and transport, into the gas grid, the hydrogen produced by the surplus of renewable sources [2]. The hydrogen's fraction strongly influences combustion parameters such as the Wobbe index and higher heating value. So, the maximum admissible value of hydrogen injected depends on the values of gas quality parameters required by regulation authorities [3].

Nowadays, analyses of gas networks focus on the compatibility between the hydrogen "green" gas and actual gas grid. In literature, only a few recent works studied gas pipelines [4, 5] and gas distribution networks [6] behavior in the presence of hydrogen or alternative gas injections.

The goal of this paper is to develop a steady-state model able to simulate gas distribution networks, considering the dependence of gas properties on the composition of the gas mixture. The present model proposes the energy gas demand approach instead of the traditional gas flow demand, which in the presence of variable gas composition, does not meet the energy required by users. The validation of the tool is performed by comparing the results to a benchmark simulation [6]. The case of study presented shows the potential of the model developed and demonstrates the relevance of these type of analyses.

2. MATHEMATICAL MODEL

Steady-state simulations of gas distribution networks are used to evaluate flow velocities into pipes, gas pressure and composition at demand nodes. These analyses are essential to predict the behavior of networks, respect gas Standard [3] and guarantee the energy requested by customers.

2.1 Gas model

The natural gas mixture is modelled by the equation of state (1). The gas constant (R_g) depends on the universal gas constant and the molecular weight of the mixture. The compressibility factor (Z) is evaluated using the Papay [7] equation (2) where T_r and p_r are the reduced temperature and pressure of the gas mixture.

$$\rho = p/Z_g R_g T \tag{1}$$

$$Z_g = 1 - 3.52\, p_r\, e^{-2.260\, T_r} + 0.274\, p_r{}^2\, e^{-1.878\, T_r} \tag{2}$$

Natural gas composition changes according to the source's location and even more in the presence of alternative gas injections. The Wobbe index represents the quality of the gas and its interchangeability. It is calculated using equation (3) where HHV_{0g} and ρ_{0g} are the high heating value and standard density of the gas mixture and ρ_{0a} is the standard air density. The Gas Safety (Management) Regulations [3] define the allowed Wobbe index range (47.2–52.2 MJ/Sm^3) to guarantee optimal combustion of the fuel in the devices connected to the grid.

$$WI = HHV_g / \sqrt{\rho_{0g}/\rho_{0a}} \tag{3}$$

2.2 Node Model

Nodal elements are the points where either the gas is injected into the network (supply node) or is delivered to users (demand node). They can also represent junctions for the pipes. For any node of the network, the algebraic sum of mass flows of each gas component (4) and of the gas mixture (5) is equal to the mass flow injected (positive) or delivered (negative).

$$\sum_{i=1}^{n} \dot{m}_{in,i} - \sum_{j=1}^{n} \dot{m}_{out,j} = \dot{m}_{dmd} \tag{4}$$

$$\sum_{i=1}^{n} y_k\, \dot{m}_{in,i} - \sum_{j=1}^{m} y_k\, \dot{m}_{out,j} = y_k\, \dot{m}_{dmd} \tag{5}$$

In this work, the energies required by the network's users are the actual boundary conditions imposed. So, the gas mass flow demand is calculated, considering the variation of the gas mixture composition, by equation (6). This method is used instead of the traditional approach, which imposed the gas flow because, in the presence of hydrogen injection, the high heating value can vary significantly from one node to the other.

$$\dot{m}_{dmd} = \rho_{0g}\, \dot{E}_{dmd} / HHV_g / 3600 \tag{6}$$

2.3 Pipe model

Pipes of gas networks are the linear elements where gas is transported from a source node to a demand node. In steady-state and isothermal condition, for the gas mixture (7) and each gas component (8), the inlet mass flow is equal to the outlet mass flow (continuity mass equation). Pressure drops along the pipe are calculated with the Ferguson [8] equation (9). This integral formulation of the Momentum equation includes the effect of the pipe inclination (θ). For turbulent flows, the Darcy–Weisbach friction factor (λ), which depends on roughness (ε) and diameter (D), is evaluated with the Colebrook–White [7] equation (10).

$$\dot{m}_{in} - \dot{m}_{out} = 0 \tag{7}$$

$$y_k\, \dot{m}_{in} - y_k\, \dot{m}_{out} = 0 \tag{8}$$

$$c_1\, p_{in}^2 - p_{out}^2 - c_2\, |\dot{m}|\, \dot{m} = 0$$
$$c_1 = exp(-c_3);\; c_2 = \frac{8\,L}{\pi^2 D^5}\, \lambda\, Z_g R_g T\, \frac{1-c_1}{c_3};\; c_3 = \frac{2\,g}{Z_g R_g T}\, L\, \sin\theta \tag{9}$$

$$1/\sqrt{\lambda} = -2\, \log\left(2.51/Re\sqrt{\lambda} + \varepsilon/3.715D\right) \tag{10}$$

3. CASE OF STUDY

In this paper, a low-pressure distribution network is studied. The natural gas (M_{NG} = 16.4790 kg/kmol) is introduced into the network from two sources (nodes 1 and 18) at a relative pressure of 0.50 bar and a temperature of 15°C. The network delivers 620 Sm^3/h to three industrial users (nodes 4, 5 and 10) and 415 Sm^3/h to seven residential users (nodes 11—17), as shown in figure 1. An additional source (node 19) of H_2 (M_{H2} = 2.0159 kg/kmol) is added to analyze the impact of the injection of alternative low carbon gases on network's thermodynamic parameters and quality of gas supplied to customers. Table 1 shows nominal gas demand by each user node and pipe data (D and L). For all nodes, the sea level altitude is assumed. Moreover, each pipe of the network has a roughness of 0.01 mm.

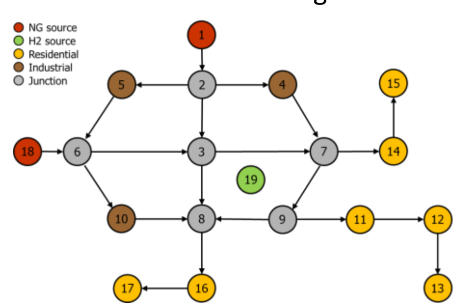

Fig 1 Network scheme

Figure 2 shows the relationship between the high heat value and the Wobbe index for the different compositions of the NG and H_2 mixture. Increasing hydrogen mass fraction, the HHV and WI of the gas mixture decrease. The Wobbe index is close to the minimum admissible value when the H_2 into the mixture is 5%.

Node	$\dot{Q}_n$ [Sm³/h]	Pipe	D [m]	L [m]	Pipe	D [m]	L [m]
4	230.00	1-2	0.16	200	8-9	0.11	350
5	180.00	2-3	0.16	500	8-10	0.11	350
10	210.00	2-4	0.11	350	9-11	0.08	100
11	50.00	2-5	0.11	350	11-12	0.08	100
12	75.00	6-3	0.16	500	12-13	0.08	100
13	35.00	3-7	0.16	500	7-14	0.08	100
14	45.00	3-8	0.16	500	14-5	0.08	100
15	90.00	6-5	0.11	522	8-16	0.08	100
16	65.55	7-4	0.11	522	16-17	0.08	100
17	55.00	6-10	0.11	522	18-6	0.16	200
		7-9	0.11	522	19-N_{inj}	0.16	283

Tab 1 Network characteristic

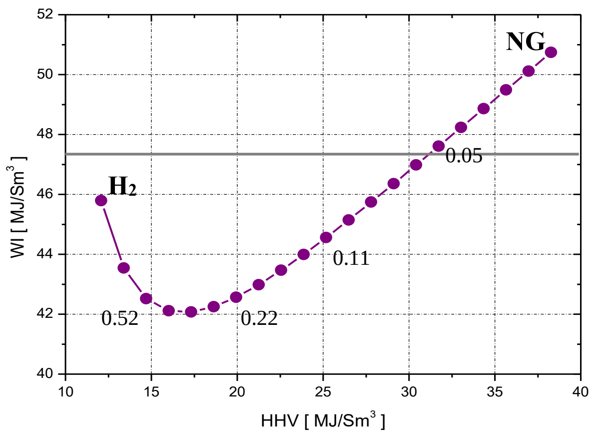

Fig 2 Wobbe index vs HHV

Gas demand profiles of users connected to the grid are showed in figure 3. Gas demand by industrial users is constant and maximum during the day when factories work at full load. Instead, for residential users, gas demand is variable. There are three peaks of demand (morning, lunchtime and evening) when all people use gas for cooking and heating their homes. In the other hours of the day, the natural gas is used, not simultaneously, by only some customers. So, the gas demand is smaller than the nominal demand.

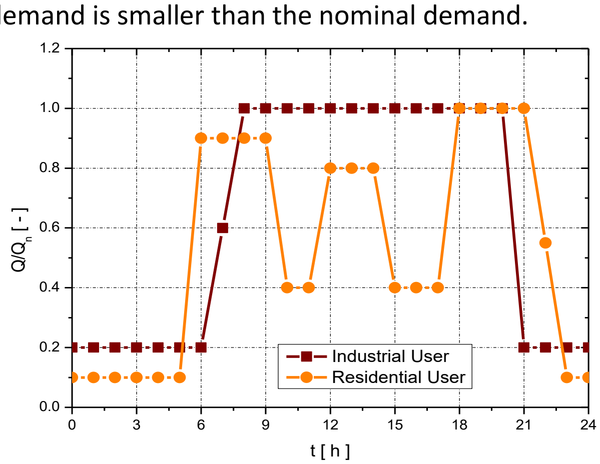

Fig 3 Gas flow profile

4. RESULTS

When alternative gas sources are used in a gas grid, it is essential to study how the amount of energy injected and the position of the injection impact on the gas network parameters. Furthermore, the gas demand and consequently flow parameters of the network change during the day. So, the nominal case is not sufficient to predict the real influence of alternative gas injection on network behavior.

4.1 Nominal Gas flow Demand

In this paragraph, six different locations of the hydrogen source are analyzed. An amount of H_2 energy until 600 kJ/s (about 5 % of the total energy) is injected into the network at a pressure equal to the node connected and a temperature of 15 °C. Figure 4 and 5 show minimum relative pressure and Wobbe index predicted by simulations. Minimum pressure and WI of users for the reference case are respectively 0.4836 bar and 50.74 MJ/Sm^3. Increasing the amount of hydrogen injected, the pressure of user nodes decreases. With a higher fraction of H_2, the HHV of the gas mixture delivered is lower. So, a higher gas flow, which produces more significant pressure drops, is required to satisfy the same energy demand. The injection at node 9 is the most unfavorable solution. If a maximum pressure loss of 3.5 % between the source node and users is allowed, the maximum energy injected at node 9 is about 240 kJ/s. Instead, minimum effects are produced if the H_2 source is located at node 7. The Wobbe index is highly influenced by the composition of the gas mixture, as previously noted in figure 2. It decreases with the amount of hydrogen injected. In the case of injections at node 2, 3 and 6 values are included in the acceptable range [3]. For the other solutions, an injection of 600 kJ/s does not guarantee the minimum WI value allowed. If the hydrogen source node is connected to node 9, it is possible to inject only about 180 kJ/s.

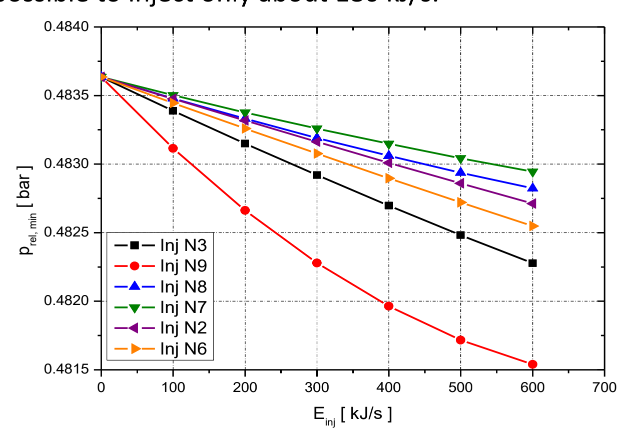

Fig 4 Minimum pressure of network users

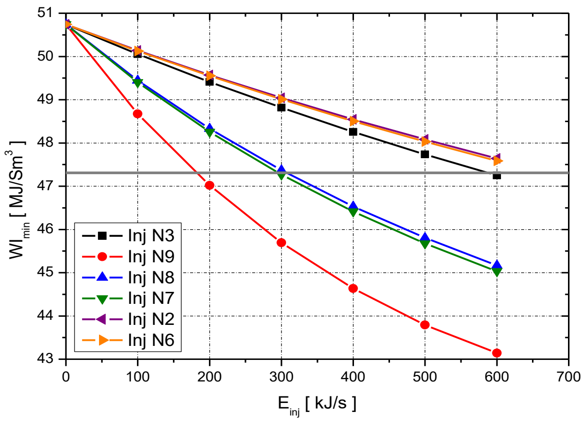

Fig 5 Minimum WI of network users

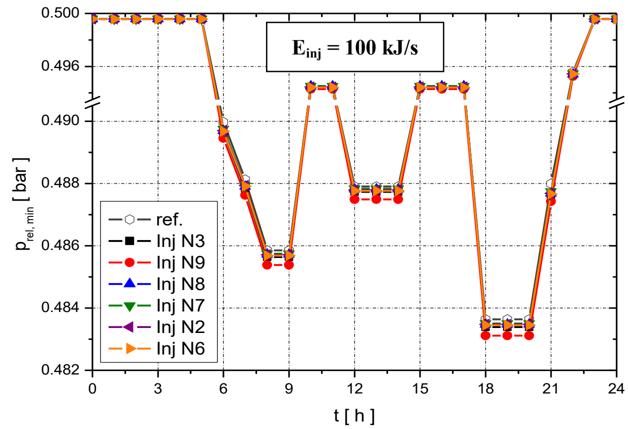

Fig 6 Minimum pressure of network users during the day

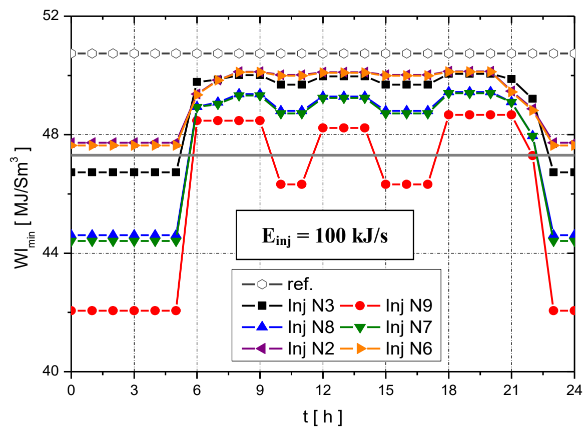

Fig 7 Minimum WI of network users during the day

4.2 Gas flow Demand during the day

The network is simulated at each hour of the day to analyze the different demand scenarios. Gas flow demand profiles of figure 3 and the same pressure and temperature of the natural gas sources are imposed.

Results of the simulations for a 100 kJ/s of hydrogen injected are displayed in figure 6 and figure 7. Pressures of the network increase when lower gas demand is required and vice versa. Maximum differences, between the reference case and the injection solutions, are during the peaks of demand. For the other hours of the day, pressure losses are minimum, and a hydrogen injection does not affect the pressure at the demand nodes. During the hours of minimum gas flow demand, the percentage of hydrogen injected increases compared to the total energy injected into the network and the H_2 fraction of nodes increases too. As a consequence, the minimum Wobbe index of user nodes decreases. For the injections at node 3, 7, 8 and 9, the minimum admissible value of WI is not respected at all hours. The minimum WI value during the night is about 14% lower than the value of the nominal simulation.

5. CONCLUSIONS

A steady-state model to analyze a gas network in the presence of alternative fuel injection was developed. In this paper, the model was utilized to simulate a low-pressure gas distribution network with two natural gas source and one hydrogen gas source. Results show that pressure and Wobbe index highly decrease when hydrogen gas is injected into the network. However, an appropriate choice of position of the injection source reduces the impact on the network. The allowed amount of H_2 injected changes during the day due to the different gas demand by users. So, only the analysis of the nominal case does not guarantee the respect of gas Standard at each hour of the day.

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