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Simulation and analysis of low pressure gas networks with decentralized fuel injection

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Abstract

Understanding the impact of injecting substitute fuels in the gas distribution network is important in the transition to a low carbon energy supply. A model was developed to identify the effects of decentralized, alternative fuel injections on the steady state operation of the low pressure gas network. A case study was designed to investigate the impact of hydrogen injection on the network compared to the normal operation. The results show the sensitivity of the network pressure distribution and the penetration of hydrogen to the amount and location of hydrogen injection. The study shows that the impact of hydrogen injection can be localized and managed by appropriately choosing the location of injection.

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Keywords: gas networks, steady state analysis, interchangeability, hydrogen injection

1. Introduction

In a variety of UK's future energy scenarios, blending of alternative low carbon fuels (upgraded biogas, hydrogen, etc.) in the gas network is recognized as a potentially important part of the low carbon future [1]. Similar to integrating distributed generation in electricity networks (solar photovotaics etc.) the gas system can reduce its carbon footprint by absorbing locally available low carbon alternatives into the natural gas network. However, distributed injection of low carbon alternatives will alter the gas transportation properties (pressure and flow rate) and thermodynamic parameters of the present natural gas mixture [2]. The variation in gas composition can affect the consumer appliance functionality and the operating strategy of the gas network [3]. Simulation of the gas network is important to understand the operational states of the network under varying conditions. Methods for a comprehensive analysis of the gas network with decentralized, alternative fuel injection have not been reported.

This paper presents a method that has been developed to perform a steady state analysis of the low pressure gas network with distributed injection of low carbon alternatives.

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2. Gas interchangeability

Key gas quality requirements to be maintained in the UK gas mains are specified in the Schedule 3 of the Gas safety (Management) regulations [4]. Gas quality requirements are specified in terms of the requirements for both pipeline integrity and combustion. This study is focused on the delivery of thermal energy for combustion aspects of gas. If gas appliances can perform satisfactorily with different gases without materially changing their safety, efficiency and operability, then the gases are interchangeable [5]. The Wobbe Index is the key parameter used to compare interchangeability of dissimilar gas blends. It is defined as

$$\text{Wobbe Index (WI)} = GCV / \sqrt{SG} \tag{1}$$

where GCV denotes gross calorific value and SG specific gravity of the gas mixture. The ‘Wobbe Index’ is expressed in the same units as that of the gross calorific value (mega jules per standard cubic meter). The WI for natural gas supplies in the UK is maintained between 47.2 – 51MJ/m^3 as specified by the Gas safety management regulations [4].

If two fuels have identical Wobbe Indices, then for a given pressure and valve setting the thermal energy input will also be identical. However, it is important to note that maintaining the pressure and the Wobbe index alone is not sufficient to ensure satisfactory combustion. Other considerations such as flame speed and flame temperature should be considered on a case by case basis.

3. Method

The method determines the steady state operational parameters of the gas network with alternative fuel injections at distributed locations. Steady state is a snapshot of the network where the parameters characterizing the flow of gas are independent of time. The structure of the model is shown in Figure 1.

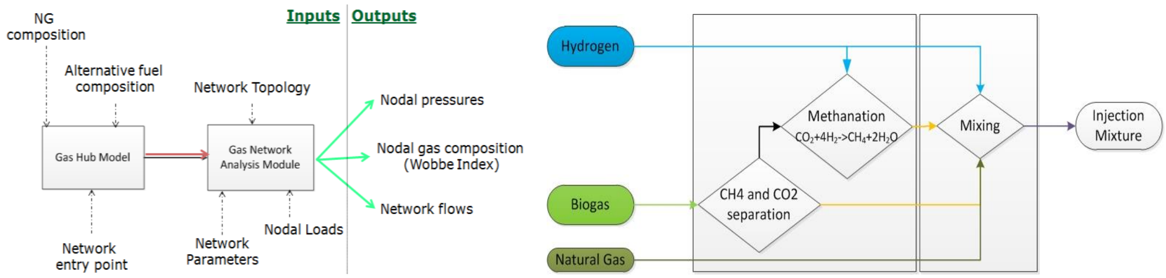

Figure 1: a) Structure of the model b) Gas hub model

It consists of two parts

- Gas hub model – the model for specifying the location and type of the alternate gas to be injected, and
- Gas network analysis module – the algorithm for the steady state analysis of gas networks.

The gas network topology, pipe parameters and energy demands are specified as inputs to the ‘gas network analysis module’. The location and type of the alternate gas to be injected to the network are specified as inputs to the ‘gas hub model’. The quantity of alternative gas injected is either specified as a fraction of the main gas flow at the point of injection or as a negative energy demand. The ‘gas hub model’ calculates the gas mixture composition at the point of injection and the ‘gas network analysis module’ performs a steady state analysis of the network.

Due to the dissimilarity in gas composition that may occur with distributed injection the algorithm was developed to meet the energy requirement at each demand node as opposed to gas volume demands used in the conventional analysis [6]. A set of initial approximations for nodal pressure are iteratively corrected using the Hardy Cross method published in [7] . Gas volume flow in each pipeline is calculated using Lacey’s equation for low pressure networks between 0-7500Pa gauge [6]. Steady, isothermal flow and constant compressibility of gas and constant friction coefficient over the length of the pipe is assumed.

$$V = 5.72 \times 10^{-4} \sqrt{\frac{\left[(p_1 - p_2) \times D^5\right]}{f \times SG \times L}} \quad (2)$$

V-Gas volume flow rate, *p*–Pressure, *D*-Diameter of pipe, *f*–friction factor, *L*–Length of pipe
The value of *f* is determined from Unwin's low pressure formula [6]

$$f = 0.0044\left(1 + \frac{12}{0.246D}\right) \quad (3)$$

The specific gravity is calculated for the gas composition at the node with a higher pressure in the pipe segment considered. The algorithm includes formulating a pipe analysis order in each iteration to consider the mixing of two gas streams meeting at a node. Perfect mixing was assumed and the outflowing gas stream/s to have a uniform composition. Energy conservation and mass conservation equations were applied at mixing instances to calculate the outflow gas stream properties. The iterations continue until the flow balance error at each node is less than a specified tolerance for the calculated nodal pressures.

4. Case study

A case study was developed to investigate the impact of hydrogen injection into the low pressure gas network. The network diagram is shown in Figure 2. Table 2 lists the cases that were analyzed.

Table 1: Nodal energy demand and source pressure for the case study (Reference case)

Node Number	Load (kJ/s)	Pressure (Pa)	Node Number	Load (kJ/s)	Pressure (mbar)
1	0	7500	8	2500	-
2	2500	-	9	0	-
3	2500	-	10	0	-
4	2500	-	11	625	-
5	2500	-	12	625	-
6	2500	-	13	625	-
7	625	-			

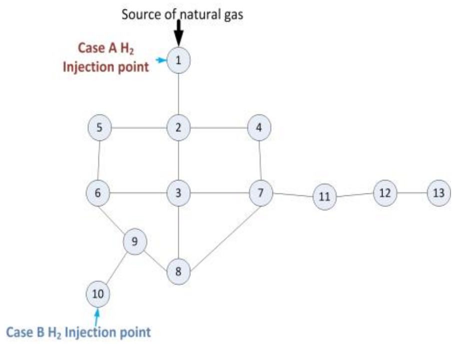

Figure 2: Case study network

Table 2: Case studies

Case	Network entry point for hydrogen	Amount injected
Reference	No hydrogen injection	-
A	Node 1	5%, 10%, 15%, 20% of the total gas volume inflow
B	Node 10	100kJ/s, 200kJ/s and 400kJ/s of hydrogen energy

5. Results and discussion

The impact of hydrogen injection on the pressure delivery and the Wobbe Index were analyzed. In case A, it was observed that the pressure downstream is affected unfavorably (Figure 3). With an increasing volume fraction of hydrogen in the gas blend, the downstream pressure reduces further. The higher pressure gradient observed with hydrogen injection is a result of increasing volume flow through pipes. Blending hydrogen at node 1 reduces the calorific value of the gas mixture delivered downstream. Therefore, to meet the same energy demand a higher volume flow rate of gas needs to be maintained. Therefore, a higher pressure drop is observed.

Table 3: Wobbe index in the network with injection at node 1 and node 10

	Reference case	Case A			
		5%	10%	15%	20%
@ all nodes	52.8	52.1	51.5	50.81	50.15

	Case B		
	100 kJ/s	200 kJ/s	400kJ/s
@ node 6	52.8	52.8	52.4
@ node 8	51.2	49.9	48.0
@ node 9	44.6	44.0	48.3
All other nodes	52.8	52.8	52.8

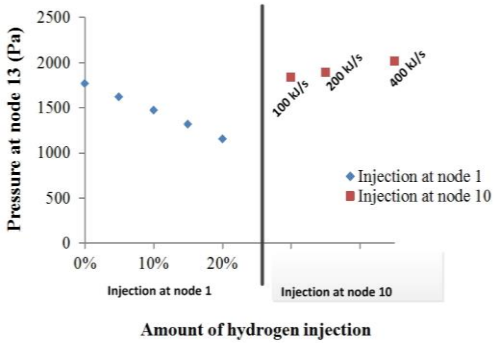

Figure 3: Variation of the pressure at node 13 for varying level of hydrogen injection

Hydrogen injection in case B has an opposite effect on pressure to the prior. At all nodes the gas pressure was increased compared to the reference case. The pressure received at the furthest consumer (Node 13) is shown in Figure 3. This is due to the reduced flow of natural gas from the source node and by accommodating the hydrogen injected from within the network.

The Wobbe Index of the source natural gas is 52.8MJ/m^3. An increasing hydrogen percentage reduces the Wobbe Index of the gas mixture. This is observed from the results of Case A, shown in Table 3. The injection of hydrogen at Node 10 (Case B) will vary the amount of hydrogen received by different parts of the network. The location and quantity of hydrogen injected and the gas demand pattern across the network will determine the spread of hydrogen. It can be seen that the effect of hydrogen injection on the Wobbe Index is only observed at demand Node 8 and Node 9 when 100kJ/s and 200kJ/s of hydrogen energy were injected but was also received at Node 6 for the 400kJ/s case.

6. Conclusions

A method for carrying out a comprehensive analysis of the steady state of a low pressure gas network was developed. The model is capable of analyzing the effects of decentralized alternative fuel injections on the operation of the network. A case study with hydrogen injection in the low pressure gas network shows the sensitivity of the network pressure distribution to the location and amount of injection. It was also shown that by selecting a suitable location for hydrogen injection it might be possible to alleviate network wide effects on the Wobbe Index.

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