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A mathematical framework for modelling and evaluating natural gas pipeline networks under hydrogen injection

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Abstract

This article presents the framework of a mathematical formulation for modelling and evaluating natural gas pipeline networks under hydrogen injection. The model development is based on gas transport through pipelines and compressors which compensate for the pressure drops by implying mainly the mass and energy balances on the basic elements of the network. The model was initially implemented for natural gas transport and the principle of extension for hydrogen-natural gas mixtures is presented. The objective is the treatment of the classical fuel minimizing problem in compressor stations. The optimization procedure has been formulated by means of a nonlinear technique within the General Algebraic Modelling System (GAMS) environment. This work deals with the adaptation of the current transmission networks of natural gas to the transport of hydrogen-natural gas mixtures. More precisely, the quantitative amount of hydrogen that can be added to natural gas can be determined. The studied pipeline network,initially proposed by Abbaspour et al. (2005) is revisited here for the case of hydrogen-natural gas mixtures. Typical quantitative results are presented, showing that the addition of hydrogen to natural gas decreases significantly the transmitted power : the maximum fraction of hydrogen that can be added to natural gas is around 6 mass percent for this example.

Key words: optimization, compressor, pipeline, hydrogen, natural gas

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1 Introduction

Confronting more and more today's urgent environmental challenges, such as the control of the release of the gases with greenhouse effect, and facing with the ever-increasing shortage in the fossil resources, the radical changes in energy policies seem now inevitable. Among the various domains, hydrogen is

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one of the energy alternatives full of promise. Preliminary studies have shown that the transport of a mixture of natural gas and hydrogen is possible through the existing natural gas networks without pipeline modification as long as the mass fraction of hydrogen remains sufficiently low (Castello et al. (2005)). Although hydrogen substitution perturbs little the fluid mechanics constraints of the system, the limitations fall into the tolerance of the construction materials of the pipes, compressors and other elements of the natural gas infrastructures. This work is exclusively interested in the transmission pipeline of hydrogen gas and, more exactly, in the adaptation of the current transmission networks of the natural gas to hydrogen transport.

The transition towards the situation in which hydrogen becomes an important energy carrier (Seymour et al. (2008)), needs decades but worldwide great efforts are made in the field of hydrogen production, delivery, storage and utilization. In this view, an analysis of the potential of using the actual natural gas pipeline systems for the delivery of hydrogen is a valid argument. Defining the conditions under which hydrogen can be added to natural gas constitutes a first step of this investigation. The chemical and physical properties of hydrogen and natural gas differ significantly, which have an effect on safety related to gas transport and its utilization as well as on the integrity of the network.

Some authors have examined hydrogen transport by pipeline and a few reports (for instance, Castello et al. (2005), Smit et al. (2007), Tzimas et al. (2007), Haeseldonckx and D'haeseleer (2007)) discuss the use of existing natural gas pipelines to transport hydrogen or hydrogen-natural gas blends. It has been highlighted by previous researchers (Oney et al. (1994)) that this can be performed under certain conditions (mainly high production pressures and large enough markets) to be economically feasible over long distances.

These are also the main objectives of the NATURALHY-project (supported by the European Commission within a Thematic Priority on Sustainable Energy Systems of the Sixth Framework Programme) which investigates the conditions under which hydrogen can be added to natural gas with acceptable consequences for safety, life cycle and socioeconomic aspects, durability of the system, gas quality management and performance of end-user appliances (Florisson et al. (2006)).

Among the recent works, the influence of hydrogen on the pressure drop in the pipelines has been calculated by Schouten et al. (2004). In Parker (2004), the construction costs of natural gas transmission pipelines have been analyzed and the impact of hydrogen in the global cost has been studied. From an economic viewpoint, the cost of natural gas pipelines is a function of pipe diameter and the cost of a hydrogen pipeline can be 50%-80% higher than that of a natural gas pipeline of the same size (Veziroglu and Barbir (1998)). Regional transportation costs could be as much as five times higher than natural gas, primarily because of the lower volumetric energy density of hydrogen (Whaley (2001)). Besides, hydrogen embrittlement of the steel under the high pressures environment of hydrogen constitutes a major concern: consequently, the transportation of a hydrogen-rich gas requires a great attention since hydrogen embrittlement is characterized by a loss of ductility of a steel (Sherif et al. (2005)).

The remaining sections are devoted to the modelling of gas pipeline networks and to the influence of hydrogen injection in natural gas infrastructures. The general context is then proposed in Section 2. This paper has not the ambition to give an answer to all questions that may arise, but may help to approach the potential challenges of the exploitation of hydrogen as an energy carrier using current pipeline systems. The model used for gas transport and extended to the case of natural gas-hydrogen blends is the core of Section 3. The optimization procedure has been implemented by means of a nonlinear programming method involving the CONOPT resolution module within the GAMS environment (Brooke et al. (1988)). A case study then illustrates the methodology in Section 4. The possibility of low amounts of hydrogen injection into natural gas pipelines will be analysed from a process engineering viewpoint. The quantitative estimation and analysis of the maximal hydrogen contents that are acceptable in the transported gas passing through the existing infrastructures of the natural gas transmission and distribution are determined. Some typical results are then presented and discussed in Section 5. Conclusions and perspectives are finally given in Section 6.

2 General context

2.1 Towards a hydrogen economy

In a world where energy demand is growing at unprecedented rates, pipelines will continue to play an important role in safely and efficiently transporting oil and gas from often remote areas to their markets. Hydrogen is foreseen as an important and reliable energy carrier in the future sustainable energy society. This energy vector, which can be produced from different primary sources among which the renewable energies, is exploitable in different stationary or portable applications. Hydrogen deployment scenarios can be based on one of two different fundamental assumptions concerning the level of decentralization in production. Regardless of the primary energy sources and technologies used, hydrogen can be produced either at large scale facilities and then distributed to individual customers over a range of few tens to some hundreds kilometers (centralized production), or in the proximity of dispensing facilities or end-use appliances (on-site generation). Consequently, this yields principally to two separate families of production and distribution pathways made of neighbouring stages allowing the adoption of different technologies.

Gaseous hydrogen can be transported using several modes like pipeline, railroad, tanker truck, and tanker ship. The chosen method depends on the distance of transportation, the production method, the use, etc.... Regarding transportation of hydrogen, along with conventional means, transportation via pipelines has been employed to make hydrogen available to a specific range of mass consuming users.

Of course, the idea of adding hydrogen to gas via pipelines to satisfy the increased demand for energy will require changes in the natural gas pipeline infrastructure to enhance the reliability of the existing systems.

According to the analysis of the dedicated literature concerning hydrogen, it is foreseeable that the hydrogen economy will have to rely on a combination of different delivery options and the share of application of each option will change and evolve with time. This study only considers hydrogen-natural gas mixture transmission via pipeline networks. Thorough technical and economic studies on the whole energy chain including production, storage, transport, distribution and utilization are the first steps to provide new industrial perspectives.

2.2 Differences between the properties of hydrogen and natural gas

The physical and chemical properties of hydrogen differ significantly from those of natural gas. Tab. 1 shows some indicative values of relevant properties for the gas chain from source to end user (some of them will be used in the development of the model). As a result of these contrasting properties, a system designed for natural gas cannot be used without appropriate modifications for pure hydrogen, and vice versa. Even the addition of a certain percentage of hydrogen to natural gas will have a direct impact on the combustion properties, diffusion into materials and the behaviour of the gas mixture in air. These aspects are considered further below.

The addition of hydrogen to the natural gas modifies its transport and calorific properties (Schouten et al. (2004)). Besides, a gas with higher hydrogen content can have an impact on the safety of the transmission-distribution-utilization chain, the durability and the reliability of the gas pipeline and the utilization performances for the end user.

	Hydrogen, H_2	Methane, CH_4	Unit
Molecular weight	2.02	16.04	g/mol
Critical temperature	33.2	190.65	K
Critical pressure	13.15	45.4	bar
Acentric factor	-0.215	0.008	-
Vapour density at normal boiling point	1.34	1.82	kg/m^3
Vapour density at 293 K and 1 bar 139 bar	0.0838 10.58	0.651 111.2	kg/m^3 kg/m^3
Heat capacity at constant pressure at 25C	28.8	35.5	J/mol-K
Specific heat ratio (C_p/C_v)	1.4	1.31	
Lower heating value, weight basis	120	48	MJ/kg
Higher heating value, weight basis	142	53	MJ/kg
Lower heating value, volume basis at 1 atm	11	35	MJ/m^3
Higher heating value, volume basis at 1 atm	13	39	MJ/m^3
Maximum flame temperature	1800	1495	K
Explosive (detonability) limits	18.2-58.9	5.7-14	vol% in air
Flammability limits	4.1-74	5.3-15	vol% in air
Autoignition temperature in air	844	813	K
Dilute gas viscosity at 299 K	9.10^{-6}	$11.\ 10^{-6}$	Pa.sec
Molecular diffusivity in air	$6.1\ 10^{-5}$	$1.6\ 10^{-5}$	m^2/sec

Table 1

Comparison between physical properties of hydrogen and methane as the principal constituent of natural gas (Baade et al. (2001), Smith and Ness (1988), Padro and Keller (2001), Rivkin (2006), Zeberg-Mikkelsen (2001), Randelman and Wenzel (1988))

In principle, hydrogen can be added to natural gas in either the high pressure, or the medium pressure, or in the low pressure distribution grid, but it must be remembered that the existing system was designed and constructed specifically for natural gas and, as explained above, the physical and chemical properties of hydrogen differ significantly from those of natural gas. In particular, the addition of hydrogen to natural gas may have an impact on the following aspects:

- **Safety related to the transmission, distribution and use of gas:** Aspects of pipeline systems, such as location, materials, wall thickness, safety devices, etc., are designed on the basis of risk assessments. For instance, the design criteria for a pipeline in a populated area differ from the criteria for a pipeline in the countryside. As hydrogen is added, it will change the gas properties and, as a consequence, the related risks will change. An additional safety risk of using a natural gas system for hydrogen may arise from the fact that the potential leakage rate of hydrogen is much larger than that of natural gas through the same sized leak (Markert et al. (2007)).
- **Integrity of pipelines:** Hydrogen may diffuse into materials and change their mechanical properties. For example, hydrogen embrittlement of steel, leading to an accelerated growth of micro cracks, is a well-recognized phenomenon. Hydrogen may also diffuse through polymers and thus result in a significant loss of hydrogen. This may affect the integrity of the system and could also have an impact on safety. A related issue concerns condition monitoring and repair techniques of the delivery system.
- **Gas quality management:** It should be ensured that end users will remain supplied with gas that meets the contractual specific cautions in order to guarantee their safety, performance of end user appliances, and billing accuracy. Moreover, this is an issue if hydrogen is extracted from the mixture, and the remaining gas is supplied to end users further downstream.
- **The performance of end user appliances:** As the combustion properties change when hydrogen is added to natural gas, this may also affect the performance of end user appliances. rs further downstream.

The remaining sections are devoted to the modelling of gas pipeline networks and to the influence of hydrogen injection in natural gas infrastructures.

3 Model extension to hydrogen-natural gas mixtures

A mathematical modelling of the gas transportation problem in networks was previously presented elsewhere (Tabkhi et al. (2006), Tabkhi (2008)). The model is enough general to take into account various gases. As abovementioned, the case of mixtures of natural gas and hydrogen is particularly examined in this paper. The pressure drop in a gas pipeline, i.e., the essential parameter to determine the required compression power for the transmission, has been derived from the differential momentum balance. Friction between fluid boundary layer and interior surface of the tube induces energy losses and, consequently, reduces the gas pressure.

The material balance and the equations of momentum conservation on the basic elements of the network as well as the other governing equations constitute the modelling core. The necessary equations in the system of the gas transmission network in order to determine the conditions such as pressure and flow rate are developed. The momentum balance for a single pipeline, the formulation related to a compressor and the associated incidence matrix deduced to facilitate the transmission network design are still applied to optimize the operating conditions.

The different links between the elementary sections of the network are defined with the use of incidence matrices. For the sake of brevity, their principle will not be recalled here (see Fig. 1 for the flowchart of the algorithm).

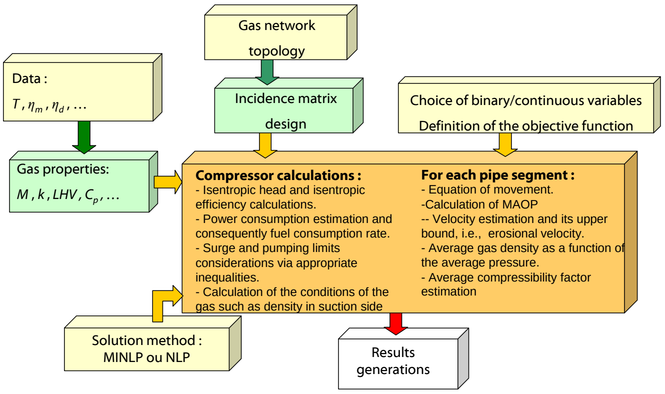

Fig. 1. Flowchart of the algorithm

3.1 Gas pipeline hydraulics

The governing equation to calculate the pressure at each point of a straight pipe can be derived as follows:

$$\frac{dP}{dx} + \frac{f\rho\overline{v}^2}{2D} + \frac{d(\rho\overline{v}^2)}{dx} = 0 \tag{1}$$

This relationship is obtained from the one dimensional momentum balance around a horizontal cylindrical control volume in steady state. The Darcy friction factor, f, is a dimensionless value that is a function of the Reynolds number, Re, and relative roughness of the pipeline, ϵ/D. The Darcy friction factor is numerically equal to four times of the Fanning friction factor that is preferred by some engineers.

Since the regime of the gas passing through pipelines lies in turbulent ranges when the flow is considered fully developed, it is assumed that the wall roughness is the limiting factor compared with the Reynolds number to find out the value of the friction factor. The friction factor is estimated from Romeo et al. (2002). The momentum balance in terms of pressure and throughput can be written in the form of the following equation:

$$\frac{dP}{dx} + \frac{8fZRTm^2}{\pi^2 MD^5 P} + \frac{16Rm^2}{\pi^2 MD^4}\frac{d}{dx}(\frac{ZT}{P}) = 0$$

(2)

By integrating Equation (2) between the points i and j, the following equation is obtained and will be used in the numerical formulations. By assuming constant temperature and pseudo-constant compressibility factor between the points i and j, the following expression can be deduced:

$$P_i^2 - P_j^2 - \frac{32ZRTm^2}{\pi^2 MD^4} ln(\frac{P_i}{P_j}) + \frac{16fZRTm^2 L}{\pi^2 D^5 M} = 0$$

(3)

This relationship between pressure and flow rate exhibits a high degree of nonlinearity. It evaluates the pressure drop corresponding to a given flow magnitude and direction. This equation is used to estimate the pipeline's pressure profile and can incorporate the pressure head that occurs due to the location of the pipeline via the elevation changes.

The compressibility factor can be evaluated using thermodynamics experimental data or calculated from appropriate equations of state such as presented in (2) for pure hydrogen (Zhou and Zhou (2001)). In this reference, the isotherms for the compressibility factor are shown as a function of pressure expressed in psi (14.706 psi = 1 bar). The compressibility factor of pure hydrogen is evaluated from the experimental P-V-T data and calculated from the Soave-Redlich-Kwong and Bennedict-Webb-Rubin equations of state. In our study, it is estimated from an empirical equation proposed for simulation goals in the literature (Mohring et al. (2004)):

$$Z = 1 + (0.257 - 0.533\frac{T_c}{T})\frac{P_{ij}}{P_c} \tag{4}$$

During the optimization procedure, the compressibility factor is considered as a function of the critical properties of the gas mixture, average pressure of the pipe segment and temperature. The case of pure hydrogen represents the extreme case. Several simulations were previously performed with this extreme case, showing that the model is not very sensitive to this parameter. This explains why a simple mixture rule is enough for the required level of precision at design level. Temperature has been considered as constant. Compared with the data presented in (Zhou and Zhou (2001)) corresponding to temperatures confronted for hydrogen pipelines, the trend of this equation is in agreement with the values obtained from state equation. Average pressure is calculated from two end pressures.

The influence of the presence of hydrogen on the pipeline hydraulic is reflected in molecular weight and compressibility factor in Equation (3). Note that the effect of the former is more significant than the latter. Since the presence of hydrogen reduces the molecular weight of the gas mixture, according to Equation (3), gas transportation by a fixed mass flow rate demands a higher pressure difference. For this reason, the pipelines transporting hydrogen require higher pressures.

The pressure at all points of the equipments should be less than the so-called maximum admissible operational pressure ($MAOP$) which is a design parameter in the pipeline engineering. To calculate $MAOP$, the wall thickness of the pipelines is considered dependent on their internal diameter according to hypothetical Equation 5. This equation gives the thickness, t, in cm for different diameters also in cm. This equation is obtained using the scheduled dimensions provided by ASME B36.19M standard that concerns stainless steel pipes.

$$t = 5210^{-3} D + 98910^{-5} \tag{5}$$

Recall that the MAOP depends also on the population density in the vicinity of the pipeline, the type of pipe material and employed welding as well as the temperature deration factor (Menon (2005)). Since the operating pipeline pressure is higher in the case of hydrogen, its transport requires thicker pipelines compared with natural gas.

An increase in flow rate due to an increase in pressure drop raises the gas velocity. An important factor in the treatment of compressible fluid flow through pipelines is the erosional velocity. This velocity is sufficiently lower than sonic or critical velocity that is the maximum velocity which a compressible fluid can reach in a pipe. In a pipeline, higher velocities in the course of a long period of time will cause the erosion of the inside surface of the tubes, elbows and other joints. Moreover, increasing gas velocity can have a particular effect on the level of vibration and increase the noises (Tabkhi (2008)). The upper limit of the gas velocity for the design purposes is usually computed empirically with the equation proposed in(Menon (2005)). The following constraint has thus been introduced in the model so that the flow velocity remains within a range where corrosion is minimized.

$$\overline{v} < \overline{v_e} \tag{6}$$

$$\overline{v_e} = 122\sqrt{\frac{ZRT}{PM}} \tag{7}$$

3.2 Compressor characteristics

The compressor stations compensate for the pressure drops due to friction in the pipelines, valves and other joints, as well as those due to elevation changes. In pipeline networks, compressor stations consume a small fraction of transported gas. The relation between suction and discharge pressures of a centrifugal compressor and the power transported to gas is represented using definition of the isentropic height of the compressed fluid. In this paper, it is assumed that the compressors performances represented by classical characteristic curves, are compatible with the case of $NG - H_2$. So, the normalized parameters h_i/ω^2, Q_a/ω, and η_i are used to describe the characteristic curves of the compressors obtained The rotation speed of all compressors is thus comprised between two bounds.

4 Case study

The example used as a test bench in this study is a didactic one inspired from Abbaspour et al. (2005), but is enough representative of the elements that may take place in gas transport. The example, initially treated for the case of natural gas, is revisited here for the case of natural gas-hydrogen mixtures. The pipeline network is presented in Fig. 2. Hydrogen is added to natural gas. The composition of the natural gas is considered constant during the optimization procedure.

This didactic network consists of three long pipelines of 100 kilometers. There are two compressor stations between these pipelines that operate to compensate for pressure drop in the transportation system. Each compressor station includes three parallel centrifugal compressors. In each station, there are six pipelines of about one hundred meters that link the compressors together in parallel. As for each compressor unit, there is a stream that carries fuel to it, there will be 6 fuel streams which have not been shown in Fig. 2 to avoid complexity. For each compressor, this stream originates from suction node. The choice of the treated example thus explains why the compressor system has been chosen (with reference to the natural gas case).

This example may be seen to some extent as a particular extreme case involving a special effort from the compressor stations, due to the high pressure drop in small pipe segments because of a lower cross sectional area than that of the main pipe segments. It can be yet emphasized that the proposed model is able to treat various cases of networks in which the compressor system is in balance with the pipelines.

The set of the specifications of the pipelines which have been introduced here as the parameters of the optimization problem is proposed in Tab. 2. In addition, the wall thickness of each pipeline is calculated according to Equation (5).

Node 0 is the supply node and gas flows from this node towards node 17. There is neither input nor output in the other nodes. The composition of natural gas is considered as shown in Tab. 3 where the thermodynamic properties of the components of gas are also presented.

The required thermodynamic properties of hydrogen are those previously given in Tab. 1. They are introduced in the formulation as additional parameters

Pipeline tag	**G1**	**G2**	**G3**	**G4**	**G5**
Diameter (m)	0.787	0.889	0.330	0.381	0.330
Length (m)	1,00E+05	1,00E+05	200	300	100
Pipeline tag	**G6**	**G7**	**G8**	**G9**	**G10**
Diameter (m)	0.330	0.330	0.330	0.381	0.330
Length (m)	200	100	200	100	100
Pipeline tag	**G11**	**G12**	**G13**	**14**	**G15**
Diameter (m)	0.432	0.330	0.330	0.330	0.838
Length (m)	100	100	400	100	1,00E+05

Table 2
Technical features of the pipelines of the system shown in Fig. 2

Component	Methane	Ethane	Propane
Mole percent	70	25	5
Molecular weight	16.04	30.07	44.1
Critical temperature, K	190.6	305.4	369.8
Critical pressure, bar	46	48.8	42.5
Lower Heating Value, kJ/kg	50009	47794	46357
Heat capacity at constant pressure, kJ/(kmol.K)	35.663	52.848	74.916

Table 3
Composition of the natural gas and the thermodynamic properties of its components

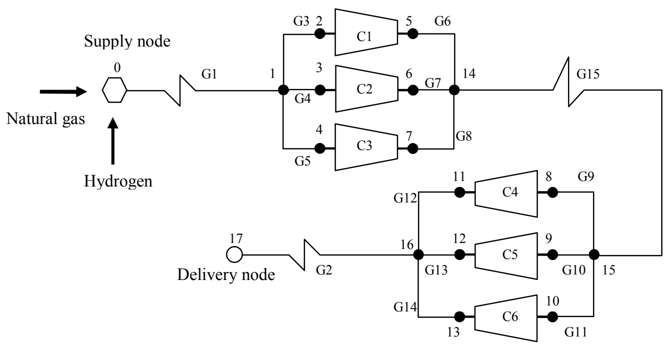

Fig. 2. Schema of the considered pipeline network to study the influence of hydrogen injection

of the problem. Dimensions of the pipelines of the network constitute other structural parameters of the optimization problem. The incidence matrixes are fixed parameters of the problem to define the configuration of the network. Roughness of inner surface of the pipes is considered to be equal to 46.10^{-6}, which is a reported value for stainless steel. A temperature of 330 K is adopted for the discharge temperature of the compressor. This is a mean value calculated by Abbaspour et al. (2005) with different type of compressor and adopted for the shortest pipelines G3 to G14. For the longest ones, the discharge temperature of the compressor is also adopted for the computation section relative to compressor stations in the model, but a standard value of 300K is taken into account for pipe segment temperature, since it was previously shown the variation in temperature is no more sensitive 10 km after the compressor station (Abbaspour et al. (2005)). Mechanical and driver efficiencies for the compressors are assumed roughly 0.90 and 0.35 respectively according to literature.

The formulation of the optimization problem relative to this example within GAMS environment involves these elements:

- Optimization variables: the basic continuous variables of this problem are: 18 pressure variables governing the nodes and 21 flow rate variables (including fuel streams) corresponding to pipes and compressors. The pressures at nodes 0 and 17 are not prefixed but they have a thin domain of variation. So practically, there are 16 pressure variables.
- Objective function: the total sum of the fuel consumption in compressors is the objective function.

- Constraints: obviously, there are two kinds of constraints consisting of:
  - Equality constraints: 18 mass balances around nodes, 15 equations of motion for the pipe arcs, 6 isentropic head equations for compressors , 6 relationships between rotational speed, suction volumetric flow rate and head of each compressor, 6 equations to calculate isentropic efficiency according , 6 equations to determine fuel consumption at each compressor unit.
  - Inequality constraints: a lower bound for delivery flow rate (flow rate in arc G2) equal to 150 kg/s, an upper bound as well as a lower bound for the pressures of the nodes: MAOP as an upper bound and atmosphere pressure as a lower bound, sonic velocity and erosional velocity in the role of upper bounds of the velocities through pipes, lower and upper boundaries on the rotation speed of all compressors (166.7 and 250 round/s respectively), a lower bound on compressor throughput taken in account to avoid pumping phenomenon, an upper bound on compressor throughput to prevent from chocking phenomenon.

The total number of variables in this optimization problem is 39. The 6 rotational speeds of the compressors have not been explicitly considered as variables, since the flow rates of the fuel streams have been already considered as variables and for each compressor this latter is directly dependent on its rotational speed. In total, there are 57 equality constraints and 76 inequality constraints.

It must be noted that the computational time is negligible in all the runs carried out for this example (inferior to 1s CPU).

5 Results and discussion

In this section, the results of the optimization problem considering the variables of the network under different operating conditions are proposed. The maximal amount of hydrogen in the natural gas is calculated for different energetic capacities of the pipeline. The first optimization criterion is based on the minimization of fuel consumption in the compressor stations. The second one is related to the maximal capacity of the pipeline in various cases.

The procedure of optimization is implemented by means of a nonlinear programming method by using the module of resolution CONOPT within the environment GAMS (Brooke et al. (1988)). Let us recall that GAMS was designed upon the principles of relational database theory and mathematical programming methods. Relational database theory provides a structured framework for developing general data organization and transformation capabilities. GAMS creates nonlinear models that will be solved with the CONOPT

Total fuel consumption rate	0.863 kg/sec
Isentropic efficiency at compressor C6	79.954
Rotational speed of compressor C6	166.7 round/s
Pressure at node 0	60.988 bar
Pressure at node 17	61.200 bar

Table 4
Initial value corresponding to some variables obtained using an auxiliary optimization problem

module, which is a NLP algorithm. GAMS/CONOPT is well-suited for models with very nonlinear constraints, which is the case in our work. CONOPT uses Sequential Linear Programming (SLP) and Sequential Quadratic Programming (SQP) algorithms (Drud, 2004). The approach is illustrated here by typical results obtained on several examples of applications.

5.1 Fuel consumption-pipeline capacity optimization (without hydrogen) as a reference

The first preliminary optimization problem is the minimization of the total rate of fuel consumption in two compressor stations simultaneously (objective function) at a constant pipeline throughput. The pressure is considered to be equal to 60 bars with a margin of ±2% at the entrance point of the network, node 0, as well as the delivery point, node 17. So the lower (respectively upper) bound of the pressure is 58.8 (respectively) 61.2 bar at these nodes.

A first computation is performed for a mass flow rate of 150 kg/sec.

The initialization of the variables is performed directly through the software (GAMS/CONOPT) under the condition that the problem is well-scaled and that bounds are assigned adequately. Yet, in this problem, the search for an initial point is a little difficult, because the variables are linked together implicitly within the strongly nonlinear constraints.

In order to show the interest of the optimization process, another preliminary optimization problem is solved via GAMS/CONOPT to produce an initial point for the main problem. In this problem, the isentropic efficiency of the compressor C6 is maximized under the same conditions explained above. The whole results for this problem are not presented but some significant ones are presented in Tab. 4.

Once the network operation problem has been formulated as an optimization problem as outlined above, it was solved using GAMS environment. Since the

Node	Pressure (bar)	Node	Pressure (bar)	Node	Pressure (bar)
0	61.200	6	66.919	12	65.510
1	47.359	7	67.030	13	65.186
2	47.042	8	58.324	14	66.809
3	47.122	9	58.260	15	58.386
4	47.192	10	58.354	16	65.072
5	67.018	11	65.185	17	58.800

Table 5
Pressure of natural gas at all of the nodes of the pipeline network

Arc	Flow rate (kg/s)	Arc	Flow rate (kg/s)	Arc	Flow rate (kg/s)
G1	150.750	G6	49.186	G11	50.343
G2	150	G7	50.450	G12	50.200
G3	49.367	G8	50.559	G13	49.521
G4	50.637	G9	50.264	G14	50.279
G5	50.746	G10	49.587	G15	150.195

Table 6
Optimal values of the flow rate for each pipeline

problem is nonlinear, the CONOPT solver has been chosen. The resolution takes less than 1s CPU on a PC which is quite acceptable. Tab. 5 presents the results relative to pressure computation at each node. Observe that at node 0 (i.e., supply node), the algorithm has taken the maximum possible pressure (61.2 bar) whereas it has taken the minimum possible value (58.8 bar) at node 17 (i.e., delivery node).

The value of objective function, that is the total fuel consumption in the compressor stations, is equal to 0.750 kg/s (sum of individual compressor consumptions, (see Tab. 8) which represents a significant reduction of 15% from the initial solution (0.863 kg/s) which may represent a viable solution for the practitioner. The values of the optimal flow rates through pipelines are presented in Tab. 6.

In this case, the relative gas consumption in the stations (in mass percentage of the input gas) is equal to 0.497 %. Additional information concerning compressor operating conditions can be deduced from pressure and flow rate optimal values (see Tab. 7) concerning: discharge flow rate, rotational speed, consumption ratio, isentropic head, isentropic efficiency and individual fuel consumption of course. For each compressor, consumption ratio is defined as the fuel consumption divided by the input mass flow rate.

Compressor	C1	C2	C3	C4	C5	C6
Discharge flow rate (kg/s)	49.186	50.450	50.559	50.200	49.521	50.279
Rotational speed (round/s)	244.348	246.482	246.558	166.7	166.7	166.7
Fuel consumption (kg/s)	0.182	0.186	0.187	0.064	0.066	0.064
Consumption ratio (%)	0.369	0.367	0.369	0.127	0.133	0.127
Isentropic head (kJ/kg)	42.592	42.188	42.201	12.664	13.367	12.607
Isentropic efficiency (%)	74.917	74.215	74.207	64.195	65.331	64.101

Table 7

Optimal values of discharge flow rate, rotational speed, fuel consumption, isentropic head and isentropic efficiency for the compressor units of the network

Pressure, bar	50	60	60
Throughput, kg/sec	130.81	150	159.3
Transmitted power, MW	6387	7324	7778
Fuel consumption, % of the input gas	0.683	0.50	0.677
Objective function	Max(TP)	Min(FC)	Max(TP)

Table 8
Network optimization at two different end-point pressures (TP:Transmitted Power; FC:Fuel Consumption

Let us mention in this example that compressors involved in the second station work at their minimum rotational speeds whereas the compressors of the first station work close to their maximum speeds.

Note that the network throughput is equal to the gas mass flow rate of the arc G2. The transmitted power of the pipeline is equal to 7324 MW at this optimum point (point A in Fig. 3 and (Tab. 8)). This quantity is the product of the pipeline delivery mass flow rate and the weight basis lower heating value of the gas (48830 kJ/kg) computed as follows:

$$P_{trans} = LHV m_{G_2} \tag{8}$$

Neglecting the constraint that states the pipeline throughput is constant at 150 kg/sec, the computed minimum mass percentage of the input gas that is consumed in the stations is equal to 0.33. The transmitted power of the pipeline is equal to 5630 MW at this optimum point. The result of this problem corresponds to point B in Fig. 3.

If the pressure is now considered equal to 50 bar at the entrance point of the network as well as at the delivery point, the network is not able to transport 150 kg/sec, because of the limitations related to the lower bound of the compressors rotational speed. Using now the transmitted power of the network as an objective function (i.e., the so-called pipeline capacity maximization problem), it is observed that the maximum pipeline capacity is only 130.81 kg/sec at end-point pressures of 50 bar. It corresponds to a transmitted power of 6387 MW. For this case, the mass percentage of the input gas consumed in the stations is equal to 0.683 (Tab. 8).

Perfoming now the same optimization scheme (maximization of the transmitted power) at end-point pressure conditions of 60 bar, the transmitted power is equal to 7778 MW at these end point pressures. It corresponds to a network throughput of 159.3 kg/sec. At this maximum pipeline throughput, 0.677 percent of the supply gas is burnt in the turbines of the pressure stations. Verifying the constraints at this optimum point, it is observed that the pipeline capacity can not increase more; indeed, all compressors are working around their maximum revolution speed of 250 rotation/s. Removing this limitation by changing this upper value to 350, the pipeline capacity maximization results in a value of 169.75 kg/sec. At this optimum point, the compressors C1 to C5 are working at rotational speeds of 294.9, 343.8, 293.6, 187.9 and 171.0 rotation/s respectively whereas the compressor C6 is working at its minimum possible speed that is 166.7 round/s. At this optimum point, the gas velocities in the pipelines G3, G4 and G5 are around their maximum possible values (erosional velocity). These examinations confirm that these short pipelines are the bottleneck of the system due to their relatively small diameters as well as the compressors due to their characteristic working domains.

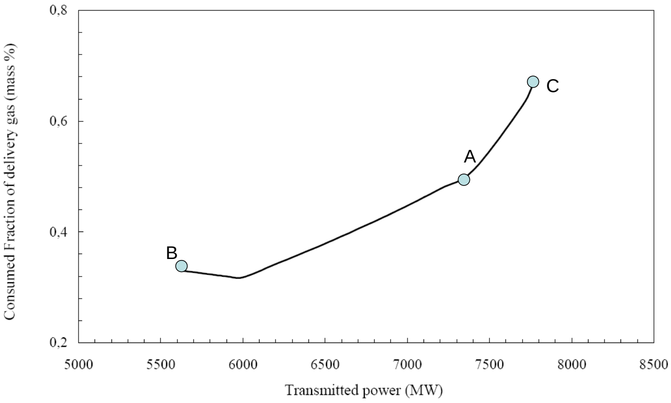

Fig. 3. Optimal problems treated for end-point pressures of 60 bars

In this problem, the fuel consumption has been kept constant in the form of a constraint. The curve in Fig. 3 expresses the optimal values of the consumed fraction of delivery gas as a function of the transmitted power at network end-points. According to this graph, increasing the pipeline transmitted energy increases the fraction of transported gas that is consumed in the compressor stations. It is necessary to say that beyond the tip point of the curve, the optimization procedure falls into an infeasible solution, as explained above.

5.2 Optimization problems in the presence of hydrogen

In this section, the gas running through the pipeline network is assumed to be a mixture of hydrogen and natural gas. The composition of the natural gas is the same as the reference problem presented above. Different operational conditions such as delivery pressure or hydrogen fraction in $NG - H_2$ mixtures can be considered as the objective function. The same structure of the network and specifications as those mentioned in Fig. 2 and Tab. 2 are used.

Initially, the gas passing through pipeline is considered pure hydrogen without natural gas. Here, the pressure is considered to be equal to 60 bars with a margin of 2% at the entrance point of the network, node 0, as well as the delivery point, node 17. After performing an optimization process whose objective function is the network transmitted power, the maximum achievable pipeline transmittable power is obtained 1272 MW that is equal to 16% of its value in the case of pure natural gas (7778 MW). In this case (point C in in Fig. 3), the hydrogen consumption as station fuel is 0.176% of the input hydrogen (10.534 kg/sec).

The observed reduction in the transmitted energy by the pipeline can be mainly attributed to the low molecular weight of hydrogen, i.e., about 10% of the value of natural gas (see Table (1) and the role of molecular weight in the equation of motion). Because the mass basis LHV of hydrogen is about 2.5 times of the corresponding value for natural gas, it reduces the impact of the low molecular weight of hydrogen on the reduction of the transmitted energy by the pipeline. Other parameters such as compressibility factor play a relatively minor role. Yet, another factor can be here highlighted: the diameters of the pipelines existing in the compressor stations are so small that it is observed that the gas average velocity tends to its upper limits (erosional velocity) in the case of pure hydrogen transport. Consequently, the mass flow rate can not increase any more.

The amount of hydrogen that can be added to natural gas is maximized at these end-pressure conditions. The results of this optimization problem are presented in Fig. 4. The maximum amount of added hydrogen is presented in mass and mole fraction versus transmitted power. Each computation point is obtained by considering the power transmitted by the pipeline as a constant via a constraint introduced in the optimization procedure. The objective function is the mole fraction of hydrogen in $NG - H_2$ mixtures. For example, if the transmitted power is fixed at 5000 MW i.e. 65% of the maximum pipeline capacity (7778 MW), the maximum fraction of hydrogen in the transported gas is 6.6% in mass basis. According to Fig. 4, the maximum transmitted power decreases linearly as hydrogen mole fraction in the gas increases.

Additional problems related to the optimization of the operating conditions can be treated with the same formulation by only changing the objective function. For instance, delivery pressure optimization for different hydrogen fractions in $NG - H_2$ mixtures is another interesting problem. Only some quantitative results are shown in Fig. 5 which are computed a supply pressure of 60 bar. In Fig. 5, each point corresponds to a hydrogen mass fraction con-

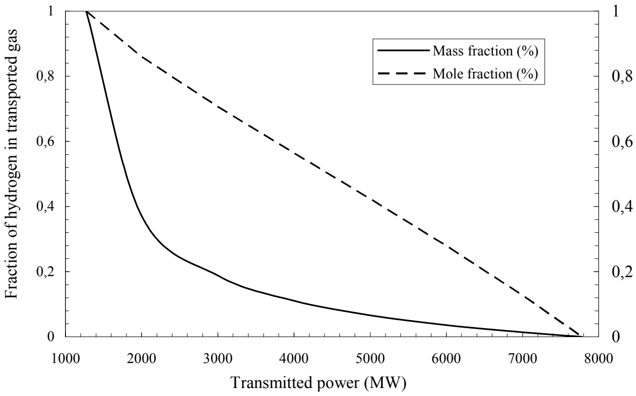

Fig. 4. Maximum hydrogen fraction in the mixture of the natural gas and hydrogen at different pipeline transmitted power for end-point pressures of 60 bar

sidered as constant taken into account via a constraint and the optimization procedure has been performed by taking the supply pressure as the objective function. The transmitted power corresponding to each delivery pressure of the pipeline network is shown on the right side axis in Fig. 5 as well.

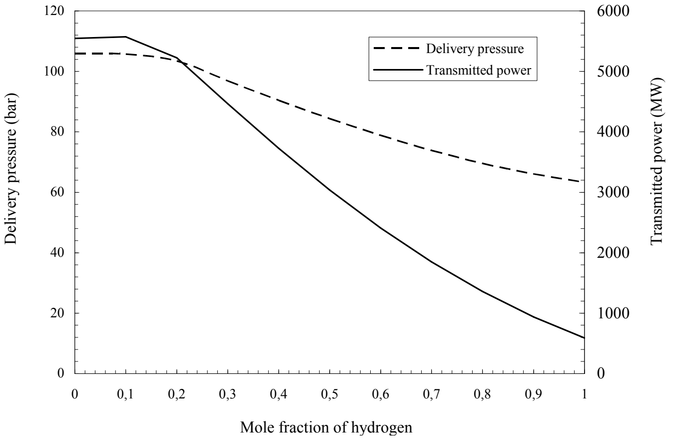

Fig. 5. Optimal values of the consumed fraction of delivery gas as a function of the transmitted power at network end-points

According to Fig. 5, for pure hydrogen transport, optimum delivery pressure is 105.98 bar and the transmitted power at this pressure is only 590.5 MW. This amount is extremely lower than the transmitted power of the pipeline for natural gas without hydrogen which is 5547 MW at this supply pressure.

6 Conclusions and Perspectives

A mathematical modelling framework for gas pipeline networks was proposed in this study. A major interest of this work is to take into account the amount of hydrogen that can be added to the pipeline network traditionally devoted to the transportation of natural gas without any modification in the system. Defining the conditions under which hydrogen can be added to natural gas constitutes a key point of this investigation as well as how much hydrogen can be injected into the existing pipeline network while minimizing fuel consumption.

The principal hydraulic limiting factor for hydrogen introduction in an existing pipeline is that hydrogen specific volume is much greater than this corresponding to natural gas which results in a strong decrease in pipeline throughput (mass flow rate) and consequently in the transmitted energy. However, a part of the reduction in transmitted energy is compensated by hydrogen LHV (weight basis) that is higher than the value corresponding to natural gas.

Several operational variables were selected as decision variables of gas pipeline optimization problem. Optimization procedures including fuel consumption minimization, amount of added hydrogen, transmitted power and delivery pressure maximization were performed for different gas mixtures of natural gas and hydrogen using CONOPT/GAMS.

It has been shown that the maximum achievable fraction of hydrogen that can be added to natural gas is around 6 mass percent for the studied example. Addition of hydrogen to natural gas decreases the transmitted power significantly.

According to this study, an adaptation of the current networks of transmission of natural gas to the transport of hydrogen seems yet possible until low values that can be quantified with optimization tools such as the model proposed in this study.

A perspective of this work is now to take into account safety constraints or criteria in the design and operation phase. In that context, the use of multiobjective optimization techniques constitutes a natural way and stochastic algorithms such as Genetic Algorithms appear as serious candidates.

7 Nomenclature

D	Pipeline diameter	m
ϵ	Pipeline diameter	
f	Darcy friction factor	-
h_i	Compressor isentropic head	m
η_i	Adiabatic efficiency	-
L	Pipeline length	m
LHV	Low Heating Value at 25C, 1 bar	MJ/kg
M	Average molecular mass of the gas	kg
M_i	Molecular mass of species i	kg
$MAOP$	Maximum Allowable Operating Pressure	
P	Segment pipeline pressure	Pa
P_c	Pseudo-critical pressure of natural gas	Pa
P_{ij}	Average pressure between two nodes i and j	Pa
Q_a	Volumetric flow rate at suction side	m$^3/s$
R	Universal gas constant	8.314 J/kmol-K
Re	Reynolds number	-
ρ	Gas density	kg/m^3
T	Temperature of natural gas	K
T_c	Pseudo-critical temperature of natural gas	K
$\overline{v}$	Average gas velocity	m/s
$\overline{v_e}$	Erosional velocity	m/s
x	Pipe centreline direction	m
ω	Rotational speed	rotation/s
Z	compressibility factor	-

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