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A NUMERICAL SIMULATION TO DETERMINE THE BEHAVIOR OF THE HYDROGEN-NATURAL GAS MIXTURE IN DISTRIBUTION NETWORKS

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ABSTRACT

This article presents the world energy situation, the importance of energy transition, and it further designates hydrogen as a potential replacement for natural gas. Moreover, the paper specifies that the energy transition will be carried out gradually, sustained by conventional resources.

Hydrogen can be mixed with natural gasses in current networks, but additional risks must be considered. These risks prove to be minimal in the distribution sector if the hydrogen fraction is kept within acceptable limits, and if optimal operation and safety measures are enforced.

The behavior of the hydrogen-natural gas mixture, also called *HENG*[1], is studied based on distinguishing the physical and chemical properties of hydrogen and natural gas. In order to analyze the true behavior of the mixture in a distribution network, a numerical simulation was undertaken, whose analysis shows that there is a tight connection between the concentration of hydrogen in the system, consumption, and *linepack*[2], and the operational limits of the network must be established based on these data.

Knowing the behavior, strategies and regulations can be drafted in order to safely exploit natural gas-hydrogen distribution networks. However, every distribution network has its own particularities, which is why additional studies both at theoretical as well as practical level, performed on real distribution networks, are needed.

Keywords: hydrogen, natural gasses, renewable energy, distribution system, numerical simulation, HENG, gas mixture, pressure, density, linepack, pipe/network *cushion*[3], caloric strength, consumer

[1]Mixture of natural gasses and hydrogen
[2]Maximum gas volume in the system
[3]Minimum volume of gas in the system to ensure flow.

INTRODUCTION

More and more countries are witnessing a growing interest in alternative energy sources. Various strategies regarding transition are being adopted, with an emphasis on decarbonization, which aims at reducing greenhouse gasses caused by coal burning, petrol products, and natural gasses.

Decarbonization strategies are very ambitious. However, as varied studies, as well as experience showed, transition towards renewable energy sources will be gradual, with petroleum and natural gasses specifically, maintaining this tendency.

Among the most important energy substitutes for petroleum, and especially natural gasses, is hydrogen, with its capacity for energy transportation, storage and utilization.

Hydrogen is not an energy source, but rather an energy carrier. Unlike natural gasses, its carbon footprint is measured by the quantity of carbon dioxide released when it is produced, and not when it is consumed.

Various studies [1] emphasize the fact that the source of the hydrogen informs the measure of the reduction of greenhouse gas emissions associated with hydrogen use. Moreover, depending on the source and production method, three main categories of hydrogen emerge. *Green hydrogen* is produced through renewable energy sources, such as the sun, wind, and water [2]. *Blue hydrogen* is produced through thermal processes for natural gas or coal conversion, associated with trapping and storing carbon, while *gray hydrogen* uses thermal sources sans carbon trapping and storing [3, 4].

It is certain that the largest portion of hydrogen used at present is being produced through methods that result in carbon dioxide, the main reason being the reduced cost of technology used for gray hydrogen production as opposed to blue and green hydrogen production. The most ubiquitous methods to obtain hydrogen are natural gas reforming, oil reforming, coal reforming, and electrolysis, with the former being the most used.

Although gray hydrogen is the most utilized form of hydrogen at present, research is underway and blue and green hydrogen production is expected to rise in the near future.

As many studies [5] show, hydrogen obtained through various methods can be utilized in almost all applications that employ the use of fossil fuels, especially natural gasses, except when carbon is specifically needed. Hydrogen is, therefore, considered a universal fuel that can replace natural gas and other fossil fuels, as they are becoming more difficult to access, and more incompatible economically and ecologically. Moreover, many publications, including those issued by *Hydrogen Council* [6] - one of the most prestigious associations worldwide, suggest that *natural gas will be gradually replaced with hydrogen* [7].

Furthermore, many web pages [8, 9] that publish articles in the energy field show that, according to *The green hydrogen economy* analysis, the global demand for green hydrogen might vary from 150 to 500 million tons/year by 2050. Production costs will drop by approximately 50% by 2030, but the rate of cost deceleration will itself slow down by 2050.

Presently hydrogen is either necessary in various industrial processes as an ingredient, or it is a byproduct. Regarding its purpose, it is used in a small number of applications. It could, however, be used to fuel transport and natural gas distribution systems, being of significant aid in the energy transition period. However, in an ambitious scenario where hydrogen will gradually replace natural gasses, dedicated installations for hydrogen production are going to be needed.

Globally there are very many ongoing projects around hydrogen, such as the European project *Hydrogen Backbone* [10] that looks at transporting hydrogen obtained from renewable energy through the European interconnected pipe networks, or the *H21 North of England* [11] project, whose purpose is replacing natural gasses with hydrogen in distribution networks. Very many studies have concentrated on efficient methods to obtain hydrogen, on analyzing hydrogen use, and on hydrogen transportation and distribution to the consumer [12].

The projects have different purposes, according to the needs of each region, but they all look at establishing the optimal operating system and safe H_2 use parameters, in order to support and promote a regulated sustainable energy market.

The article looks at the behavior of the hydrogen-natural gas mixture in distribution networks. This study considers the experiences of other authors and determines the main challenges. Finally, a simulation on a pipe network that can represent a natural gas distribution network was run. The simulation played on a number of scenarios, gradually reaching the operational limits.

CHALLENGES IN INTRODUCING HYDROGEN IN NATURAL GAS DISTRIBUTION NETWORKS

Hydrogen can be distributed through pipes using either current natural gas networks, or a new infrastructure created specifically for hydrogen. Of these two scenarios, the former is both less risky, and more economical, making it an ideal candidate for the initial stage in the process of expanding hydrogen use to a large scale, encompassing all consumer categories. This is due to the negligible hazards in case of mixtures, where hydrogen is, initially, only secondary in the mixture, but also due to moderate investments towards existing infrastructure, allowing the hydrogen market, made up of consumers and producers, time to develop. Although the scenario where hydrogen is transported alongside natural gasses through distribution networks presents smaller risks compared to when hydrogen is transported in its pure form, potential dangers must not be overlooked either. Adding hydrogen in natural gas networks elevates the already existing challenges.

In order to support a regulated energy market based on a mixture of hydrogen and natural gasses, various studies and projects have highlighted the dangers associated with HENG and have determined the optimal network operating parameters. Thus, various tests have been conducted, both theoretical, as well as practical, in order to establish several aspects regarding: the concentration of hydrogen in the natural gas mixture, how the materials making up system components and the equipment are affected by the hydrogen, as well as how to minimize leaks and potential combustion of gas in restricted mediums. Moreover, the experience of transporting hydrogen in various applications for industrial purposes represents a fair source for inspiration.

Presently, the infrastructure of natural gasses, even new models, needs small adjustments to be able to manage the HENG within optimal parameters and in complete safety.

Figure 1 schematically shows the current limitations of the natural gas infrastructure for hydrogen concentration, as well as potential limitations inferred by using equipment from other industries. Results shown are compiled from various studies [13-18] conducted until the present moment.

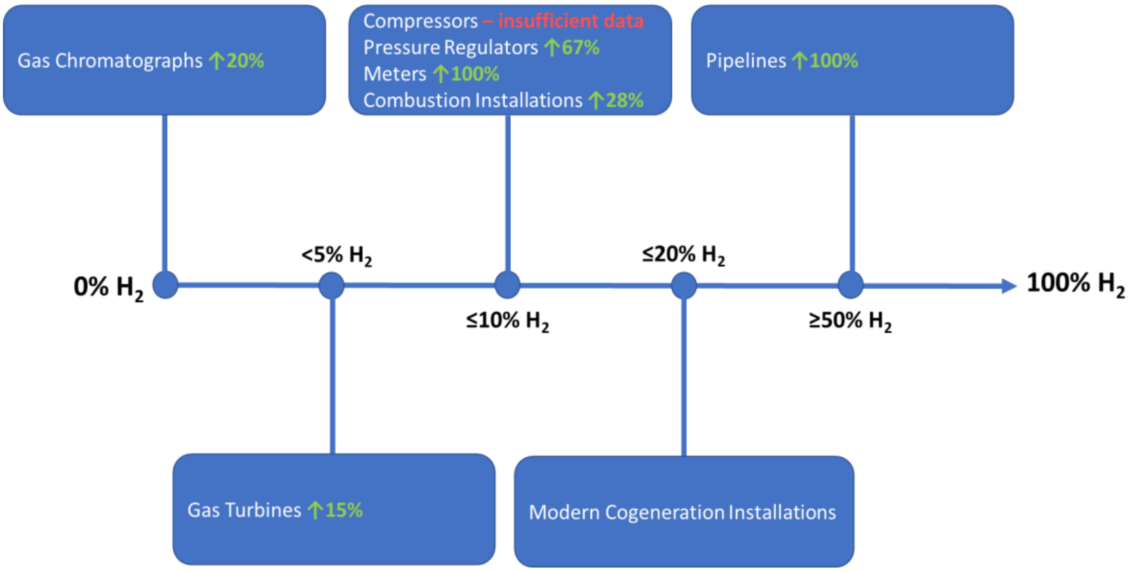

Figure 1*. Limitations of natural gas infrastructure in managing HENG*

Presently, international standards do not determine rules for hydrogen concentration limits in natural gas networks. To define these rules, in order to enact HENG transportation and distribution, further studies are required on respective issues.

Various factors closely connected to one another directly influence the functioning of distribution systems in safety conditions. A safe distribution system that is ready for hydrogen must account for both the fundamental conditions (such as the location and operating pressures), as well as for the specific properties of hydrogen (specific weight, flammability, corrosivity, caloric power, etc.). Moreover, the operating personnel must gain specific knowledge about how to operate with hydrogen, and about the potential respective hazards. For this purpose, all employees of the distribution operator, as well as contractors, should be trained regarding the new work conditions. Along with establishing new work procedures, emergency procedures will have to be re-established in order to allow the exploitation personnel and all those involved, including public authorities, to be adequately informed about the actions that must be taken in case of emergency.

As noticed in figure 1 the transport sector and final consumers are the most limited in equipment such as: gas chromatographs, compressors, gas turbines, code generation installations. However transporting HENG in distribution networks presents a diminished risk because in reasonable quantities, the system is capable of managing the hydrogen fraction, with small adaptations and improvements.

Network functioning within operational limits is that much more important when including hydrogen. Studies have shown that a network which functions within operational limits, even when the H_2 concentration is small, is operationally unsafe. Network operation is all the more difficult when the hydrogen concentration in the mixture and the consumption are higher, as there is a tight connection between H_2 intake, consumption and linepack. That is why each distribution network must be analyzed and consumption profiles must be compiled for each type of consumer.

Although hydrogen injection rhythm into the network is constant, due to varied demand of gas, variable hydrogen concentrations and pressures will emerge. Hydrogen concentration variation involves network imbalance and may lead to exceeding H_2 limits. Depending on the hydrogen source and how it is introduced in the network, its concentration may exceed the recommended volume. Studies [18] and [19] respectively, indicate that hydrogen fractions can vary in the entire network during the day if hydrogen is obtained from a renewable source such as wind-to-power and power-to-hydrogen technologies, which are owed to wind variation as well as gas consumption variation.

Storage capacity of the network will be affected by the reduced caloric power per hydrogen volume compared to that of natural gasses. Therefore, the values of pipe linepack will drop, and the volume of gasses stored for satisfying season peak consumption will be insufficient, resulting in a drop in the delivery capacity to final consumers, if the current infrastructure for natural gasses is kept. Even if the capacity of the network can be sufficient to transport hydrogen, each network has its own unique critical parameters and a revision of all final users is necessary in order to guarantee a gas quality acceptable for all consumers [18].

PROPERTIES OF THE HYDROGEN-NATURAL GAS MIXTURE

Hydrogen can be mixed with natural gas in existing networks in all pressure levels, but it must be taken into account that the existing system was designed and built specifically for natural gasses and the physical and chemical properties of hydrogen significantly differ from those of natural gasses [20]. Therefore, by adding hydrogen, the properties of the mixture will modify according to the H_2 concentration. As such, the risks and operating conditions of the network will change and additional measures will be necessary to manage the network.

BEHAVIOR OF THE HYDROGEN-NATURAL GASSES MIXTURE IN DISTRIBUTION NETWORKS

Many research papers [21] analyzed the behavior of gas flow in pipe networks. Such an analysis allows tracking stationary and transitory evolutions of network parameters and furthermore, controlling the gas distribution networks. Therefore the behavior of gas flow in pipes can be anticipated and sudden changes, which may lead to faulty functioning of the network and pipe and equipment malfunction, can be avoided. At the same time, analysis is a key characteristic in determining admissible concentrations of hydrogen in natural gas mixtures, in order to guarantee safe transportation of the gas mixture. In order to simulate the transitory flow of gasses the governing equations are solved through various numerical schemes, while more efficient solving methods are still underway.

Parameter variation in hydrogen-natural gas mixture networks. Numerical simulation

In order to produce the simulation on a distribution network, the sets of equations that govern the gas flow in pipes are solved numerically using *SIMONE (software that allows projecting, static and dynamic simulation of Gas Networks and their optimization)* [22].

For this purpose, a distribution network was designed, where the parameters that describe the gas and the pipe system (diameter, length, temperature, the composition of the gas mixture, etc.) are defined as entries. At the same time, in order to determine the behavior of the mixture in the network, several scenarios were enacted for various H_2 concentrations, and various numbers of consumers, respectively.

The model is simplified through the following hypotheses:

- neglecting density variation with pressure in isothermal conditions ((T=288,15 K = 15°C);
- singular pressure losses in pipe junctions are neglected;
- consumption is constant throughout the simulation (24hrs)
- there are no differences between the elevations of the network nodes;
- the maximum hydrogen concentration tested is 20% (amount established by many authors, in various studies [17, 18], as maximum in point of safety for the existing natural gas infrastructure).

The distribution network and simulation scenarios

The distribution network (figure 2) consists of 12 pipes and 15 nodes. The network is operated at the maximum pressure of 6 bar and presents one supply point and six consumers. The pipes have an interior diameter of 400 mm, and lengths between 0.4 km and 0.9 km.

In order to establish the composition of the gas mixture, *the simulation started from the minimum requirements for natural gas quality specified in Annex 5 to the guidelines for the measurement of natural gasses traded in Romania, approved by President Order ANRE no. 62/24.06.2008 and updated on 30.06.2011 and modified through the ANRE Order 80/21.05.2020)* [23].

Based on these data, optimal values were established for each fraction in the natural gasses mixture, and for determining the behavior of hydrogen- natural gasses mixture in distribution networks several scenarios were enacted and various simulations were run over the course of one day (24 hrs.). The scenarios differ according to the hydrogen concentration in the mixture and on the number of consumers and implicitly, the total consumption. As such, 15 scenarios were enacted according to the data in table 1.

***Table 1**. Scenarios for the simulation*

N.c. / % H_2	**NG**	**5% H2 + NG**	**10% H2 + NG**	**15% H2 + NG**	**20% H2 + NG**
6 Consumers	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5
3 Consumers	Scenario 6	Scenario 7	Scenario 8	Scenario 9	Scenario 10
1 Consumers	Scenario 11	Scenario 12	Scenario 13	Scenario 14	Scenario 15

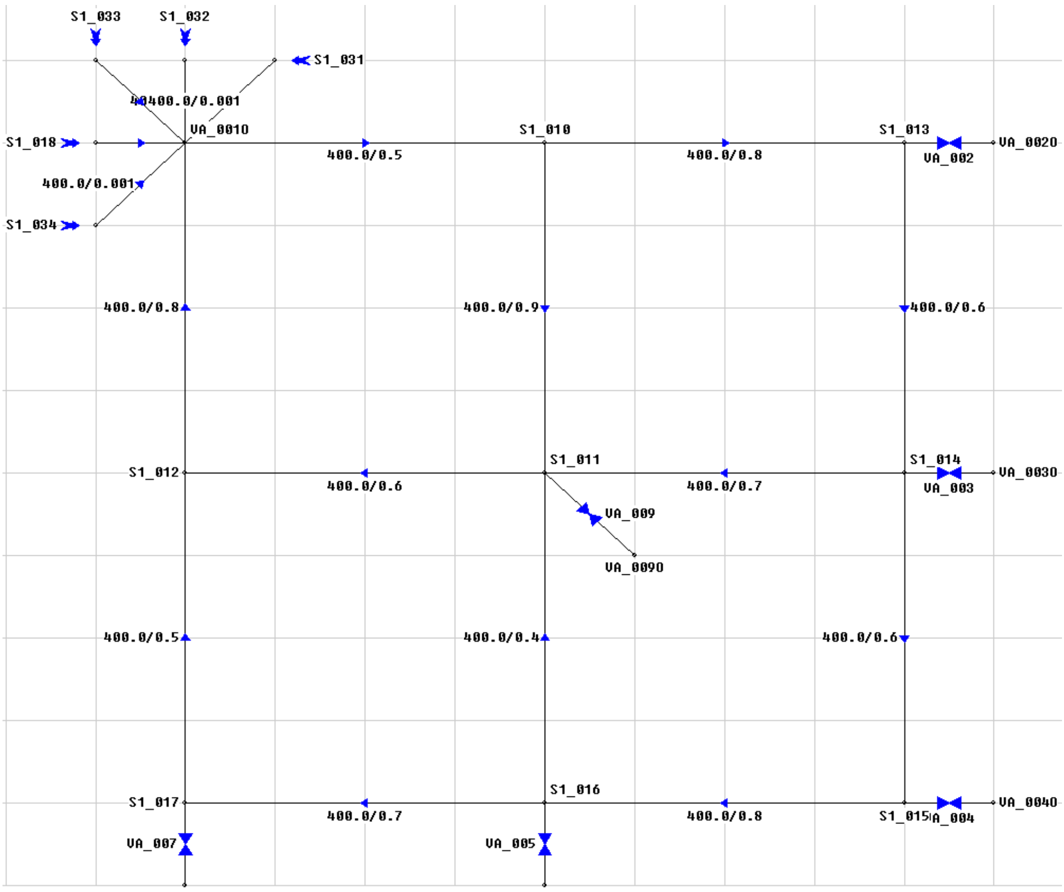

Figure 2. *Distribution network*

In order to determine the composition of each type of hydrogen- natural gasses mixture, the simulation started from the composition of natural gasses, and included the concentration of hydrogen corresponding to each scenario proportional to the other components of the gas mixture. Table 2 shows the compositions of hydrogen- natural gasses mixtures used in the simulation. It is important to note that ethyl mercaptan, or ethanethiol, is a necessary gas in identifying gas leaks, and in a real application it must not be reduced. To simplify the simulation, this component was reduced proportional to the others, considering that the results will not be significantly influenced.

Table 2. *Composition of hydrogen-natural gasses mixture used for the simulation*

Component	**0% H_2**	**5% H_2**	**10% H_2**	**15% H_2**	**20% H_2**
Methane (C1)	90,0000 %	85,5000%	81,0000%	76,5000%	72,0000%
Ethane (C2)	3,0000%	2,8500%	2,7000%	2,5500%	2,4000%
Propane (C3)	1,5000%	1,4250%	1,3500%	1,2750%	1,2000%
Butane (C4)	1,0000%	0,9500%	0,9000%	0,8500%	0,8000%
Pentane (C5)	0,2000%	0,1900%	0,1800%	0,1700%	0,1600%
Hexane (C6)	0,0700%	0,0665%	0,0630%	0,0595%	0,0560%

Heptane (C7)	0,0400%	0,0380%	0,0360%	0,0340%	0,0320%
Octane (C8)	0,0300%	0,0285%	0,0270%	0,0255%	0,0240%
Nitrogen (N_2)	2,5000%	2,3750%	2,2500%	2,1250%	2,0000%
Carbon dioxide (CO_2)	1,6476%	1,5652%	1,4828%	1,4005%	1,3181%
Oxigen (O_2)	0,0100%	0,0095%	0,0090%	0,0085%	0,0080%
Hydrogen sulfide (H_2S)	0,0004%	0,0004%	0,0004%	0,0003%	0,0003%
Ethyl mercaptan (C_2H_5SH)	0,0020%	0,0019%	0,0018%	0,0017%	0,0016%
Hydrogen (H_2)	0,0000%	5,0000%	10,0000%	15,0000%	20,0000%

Scenarios 1, 6, and 11 started from an initial state of equilibrium, where natural gas was in the network, with a pressure interval between 6 and 4.72 bar. The other scenarios were run starting from the state after the network was stabilized, after running scenarios 1, 6, and 11, corresponding to each number of consumers, so that the injection and displacing process, respectively, of natural gas with HENG of different H_2 concentrations, could be simulated.

RESULTS OF THE SIMULATION

The results obtained by running all scenarios highlight the variation of parameters in hydrogen- natural gasses networks with different concentrations of hydrogen. Therefore, the behavior of the mixture and the general conditions to stabilize the network will be determined. To emphasize the relevant changes in the system upon introducing hydrogen, certain results are represented as graphs, by comparing parameter variations (pressure drop, density, caloric power) in different scenarios. In order to benefit from accurate results as much as possible, the measurements were taken 15 minutes apart, until network stabilization.

Case: 1 consumer

This first case strictly aims at highlighting the effect of the hydrogen concentration in the mixture on the parameters. For this purpose different analyses were conducted into representative nodes of the network.

The pressure drop in the feed point *(VA_001O)* is constant throughout the day when one consumer is being fueled *(VA_002O)* cu 52,779 Nm^3/h. The result obtained indicates that in reduced consumption situations, if the network is scaled properly, adding hydrogen has no influence.

The tendency of pressure drop proportional to the hydrogen fraction added in the natural gasses confirms the results obtained by various authors, such as the authors of papers [21], and therefore, in cases of 15% hydrogen and 20% respectively, a slight drop in pressure can be observed until the network is stabilized. This is due to the different properties of hydrogen as opposed to methane. In less than an hour the network is stabilized, and the pressure becomes constant (figure 3). The density variation is further analyzed, of caloric power respectively, during one day in the same point of consumption (VA_002O), in order to highlight the influences of hydrogen contribution to natural gasses (figures 4 and 5).

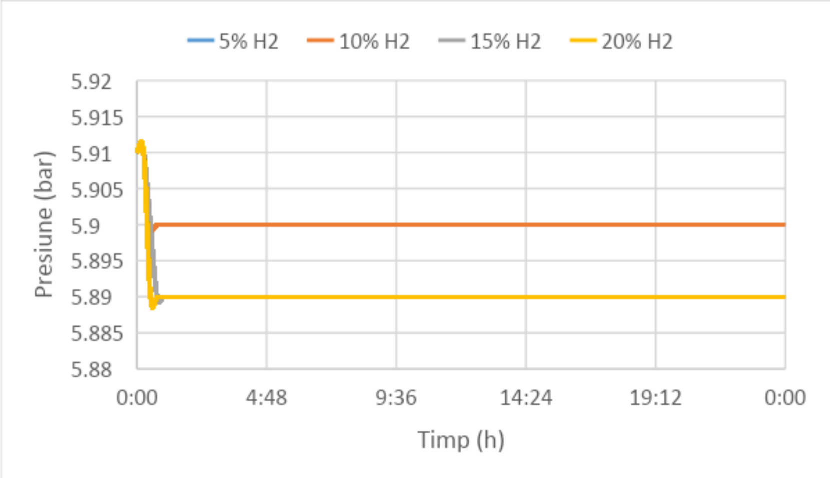

Figure 3. *Pressure variation for the consumer (VA_002O) for different hydrogen concentrations during the supply of a single consumer (Y: Pressure/ X: Time)*

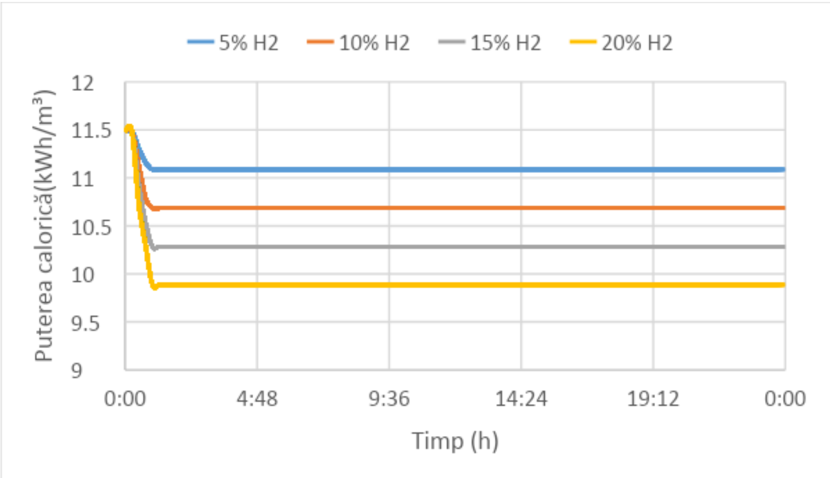

Figure 4. *Caloric power variation for the consumer (VA_002O) for different hydrogen concentrations during the supply of a single consumer (Y: Caloric power/X: Time)*

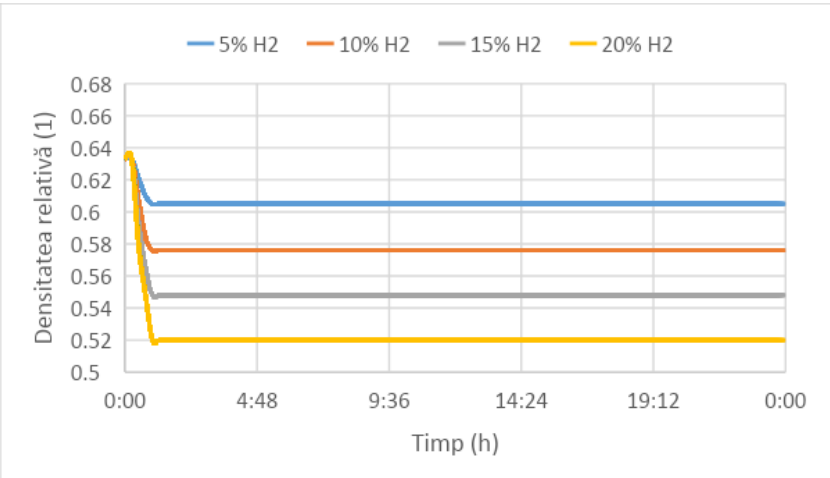

Figure 5. *Gasses mixture density variation for the consumer (VA_002O) for different hydrogen concentrations during the supply of a single consumer (Y: Relative density/X: Time)*

Due to hydrogen properties, after the network is stabilized the values of caloric power and gas mixture density drop proportional to the H_2 percentage. The most important aspect inferred from this result is that in order to ensure the power needed by consumers, it is necessary to increase the distribution network linepack, so as to maintain the power per volume unit, when the network's cushion is exceeded. A value of the pressure below the cushion limit translates into the impossibility of transporting gas through the pipes. This is all the more important as the hydrogen fraction is higher in the distribution system. Moreover, a lower value of gas density raises difficulties such as pressure leaks and incompatibility with certain equipment, previously discussed.

Case: 3 consumers

In the case of 3 consumers, the variation of parameters in the same system nodes was analyzed, in order to highlight the influence a higher consumption has on the network. In everyday life, this can translate into consumption peak periods. In creating the scenarios, the same conditions were kept as in the previous case, except for the consumption set for the other 2 consumers *(VA_009O = 43,982 Nm³/h and VA_004O = 35,186 Nm³/h).* The analysis shows that as consumption rises, pressure variation in the network becomes *steeper*. Therefore, the influence that consumption has on the network must be considered in designing a scenario for HENG distribution. The caloric strength and density parameters remain unchanged post consumption increase, because once the mixture is completed, the gas exhibits the same properties in all network nodes.

Case: 6 consumers

The last case analyzed pushes the network to the limit, by introducing a high consumption for all six consumers. The aim is to determine whether the behavior of the hydrogen-natural gasses mixture follows the same trend as in previous cases, or the high consumption will lead to additional difficulties regarding network management. In creating the scenarios the same conditions as in the previous case were kept (the case of three consumers), except for the consumption established for the other three consumers *(VA_007O, VA_005O and VA_003O).* Table 3 presents the consumption for each network consumer.

Table 3*. Actual consumption for every network consumer*

Consumer	**Actual consumption (Nm³/h)**
VA_009O	43.982
VA_007O	43.982
VA_005O	52.779
VA_004O	35.186
VA_003O	35.186
VA_002O	52.779

By pushing the network to the limit, the parameter analysis will take place for the consumer farthest from the feed point of the network *(VA_004O)*. Below are parameter variations similar to previous cases (figure 6).

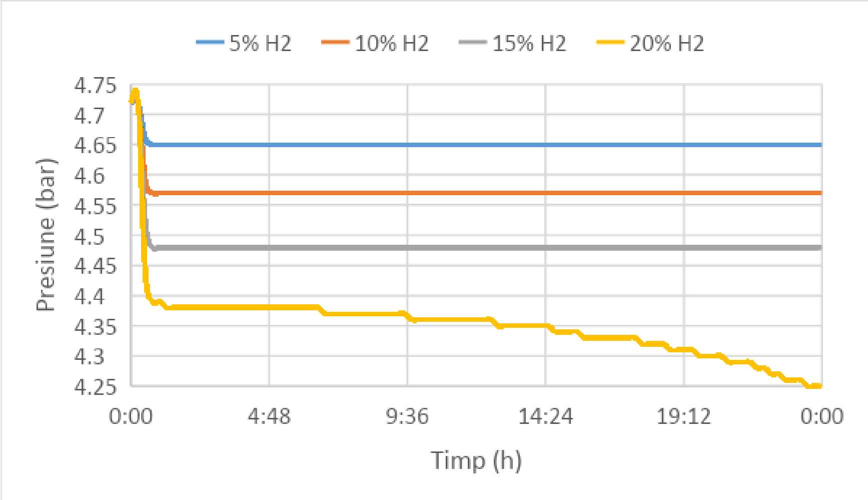

Figure 6. *Pressure variation for the consumer (VA_004O) for different hydrogen concentrations when supplying 6 consumers (Y:Pressure/X: Time)*

In regards to pressure variation, a different behavior for the 20% H_2 mixture can be observed. The pressure does not stabilize throughout the simulation, and moreover, its variation takes on a 3 polynomial-type trend. This indicates that for the 20% H_2 and 6 consumers scenario (scenario 5 in table 1), the network is not balanced, and maintaining the same high consumption without increasing transportation capacity, the value of the network linepack will tend to drop. Finally, the minimum amount of gas necessary for flow in the network will not be met and gas transportation will halt.

DISCUSSIONS

In everyday life, gas consumption is not constant. Such high consumption may be realized, for example, during certain stages of the day, while the rest of the day, the capacity may be supported from the line pack of the network. That is why consumption profiles must be compiled, that in turn will lead to nominations and allocations.

Results obtained indicate a tight relationship between hydrogen concentration, consumption, and linepack. All these must be carefully analyzed in the event of hydrogen introduction in existing natural gas systems, as it might be necessary to increase their capacity.

Over the course of the simulation (24 hrs) (figure 7), graphs depicted the variation of the mixture density in five nodes of the network, from the closest to the fueling point, to the farthest *(nodes VA_001O, S1_010, S1_013, S1_014 and S1_015)*, in order to analyze the influence of network length over the mixture of H_2 and natural gasses, for the scenario of six consumers and 15% H_2. In order for these variations to be visualized, the graph focuses on the first hour of the simulation, when the mixture is finalized in all five nodes.

The analysis result indicates that the length of the pipe influences the time needed to create the hydrogen- natural gas mixture. For a real case of a distribution network with variable consumption, this may pose an issue, as probably several fueling points may be needed to maintain the mixture as homogeneous as possible.

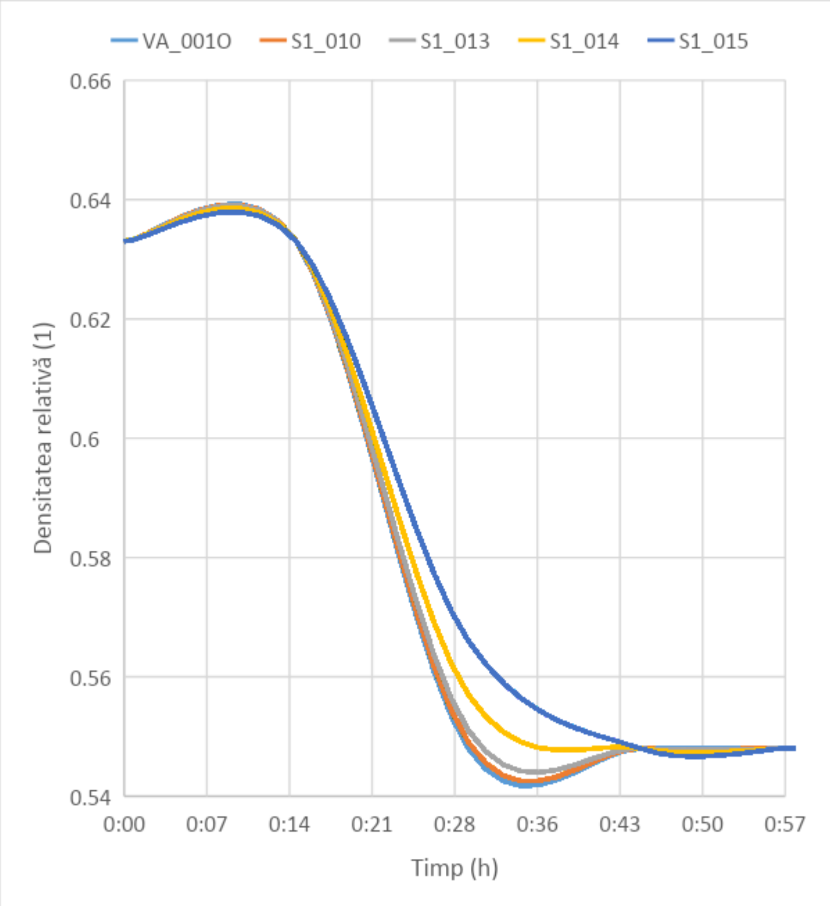

Figure 7. *Variation of gas mixture density in different nodes of the network when natural gasses in the network were displaced by HENG with 15% H2.*

CONCLUSIONS

In the introduction, the study started from the energy consumption situation, where the importance of conventional fossil resources was emphasized, as well as the importance of transitioning towards alternative energy sources, with hydrogen being designated as energy carrier and potential substitute for natural gasses. It was determined that the transition from natural gasses to hydrogen requires time, and for now, the mixture between the two is an option that can be implemented on a large scale in the near future.

Moreover, the study presented challenges regarding the introduction of hydrogen in natural gas distribution systems and noticed that by making certain modifications, the current distribution system is capable of managing the HENG at a conceptual level. At a practical level, however, further studies, simulations and tests conducted on real distribution networks are necessary.

The problems the present study focused on are hydraulic in nature. More precisely, the issues are connected to the behavior of the hydrogen- natural gas mixture in the distribution networks. For this purpose the studies started from the differences between the physical properties of hydrogen and natural gas, and the manner and extent to which these will influence the network parameters.

It was noticed that there are great differences between hydrogen and methane (main constituent of natural gasses), which will significantly influence the properties of the mixture transported through the network, and subsequently, the flow parameters, such as pressure.

Two of the most important properties of gasses (density and caloric power) were analyzed, as they have a significant impact over pressure drop, and network balance.

Following the simulation, the variation of the network parameters in the presence of hydrogen were represented as graphs. The simulation was accomplished on a pipe network that can be likened to a distribution network, and using several scenarios for different hydrogen concentrations and a different number of consumers, respectively. The results correlate with the ones obtained by various authors, which demonstrates yet again the accuracy of the information regarding the behavior of HENG in pipe networks.

In reality, however, the conditions differ from the conceptual ones, as gas consumption is not constant, with various oscillations based on the type of consumer and atmospheric conditions. To satisfy these conditions, issues associated with real distribution networks must be approached, and the consumptions should be defined based on the consumption profiles.

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