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Hydrogen-Natural Gas mixture compression in case of transporting through high-pressure gas pipelines

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Abstract. When dealing with search for ideal energy production solutions, one of the direction may be the use of hydrogen based on excess electricity. Gaseous state and the existing gas network can be used to deliver it to customers. Quantity of hydrogen in the natural gas system would be different depending on its production, hence it should be sent as an additional component sent by pipeline next to natural gas. Due to the difference in its physicochemical parameters with respect to the characteristics of natural gas, the work of gas compressors at different hydrogen concentrations will be different. An additional aspect taken into account when considering the effect of hydrogen on the performance of the compressor is the change of the main parameters which characterizes the flow. It may turn out that they will also positively influence the work of compression needed in the same compressor stations. Such changes may in consequence lead to additional savings, some of which are described in this paper.

1. Introduction

Wind turbines, often in larger numbers forming wind farms, are currently located in many parts of the world. The attractiveness of clean energy sources can be seen, for example, by significant investments in renewable energy in the case of EU Member States, in line with the priorities of the Community energy policy [1-3]. In the case of Poland, although the growth of installed capacity of wind energy has decreased in recent months, it is still increasing, giving 5 824 MW of installed capacity [3]. While potentially wind farms can provide clean electricity from wind power, two main problems arise in setting up a majority for this energy source. The first is the instability and uncertainty about the wind power, which translates into the amount of electricity generated, while the second one concerns fluctuations in market demand for this energy. These problems cause situations where there may be a shortage of power or a surplus that is usually lost due to a lack of adequate energy storage.

Surplus energy can be used under Power-to-Gas - hydrogen production from electricity [4]. Energy in the form of gas is much easier to transport or store [5]. The existing natural gas transmission network can be used for further use. Obviously, due to the differences between the physicochemical parameters of hydrogen and natural gas, there are a number of issues that need to be properly diagnosed and eliminated, such as the increased corrosivity of pipes caused by the presence of hydrogen or its increased emissivity compared to natural gas components[6]. However, research has shown that the addition of relatively low amounts of hydrogen does not significantly affect the functioning of the transmission grid, including explosive risk [7]. Moreover, less than 20% of hydrogen in natural gas does not have a significant effect on the combustion characteristics and additionally results in cleaner fuel combustion [8]. The same amount of gas has a small effect on the leakage of gas through the walls of the pipelines, and because of greater mobility from the components



of natural gas, the majority of emitted molecules, limiting in some way the emission of greenhouse gases such as methane. Other studies indicate that the maximum amount of hydrogen that will not significantly affect transport safety and use of the entire mixture is 10% [9], 20-30% [10, 8] and even 50% or more [11] depending on the criteria taken into account. It is worth noting that in the distribution networks in which city gas was used, the gas installation has been continuously exposed to hydrogen for about 50% for many years [10]. This was also the case in Poland [12].

Although hydrogen production costs are several times higher than conventional gas production costs and are unprofitable, the use of hydrogen, for example in fuel cells (high efficiency) or as a supplement to the gas system, has a great chance of success [13]. The possible transmission of hydrogen with natural gas by pipelines should, of course, be accompanied by a close link with the distribution and storage system with a continuous measurement of fuel quality to ensure adequate supply and stability of gas supply [14].

It is noteworthy that the natural gas market in Poland has grown dynamically in comparison to other EU countries in recent years, as evidenced by the increase in demand for gas in 2008-2016. In the EU, there was a 13% drop in natural gas consumption over the period (according to BP 2017). It is estimated that in the coming years, energy will be the most prospective development segment for the domestic natural gas market. However, the dynamics of market development will be determined primarily by the price competitiveness of natural gas relative to other energy carriers [15].

One of the main elements of the gas transmission system, without which it would not be possible to transport natural gas over long distances, is the gas compression stations where the gas is compressed. This process is closely related to the physicochemical parameters of the compressed substance. Since hydrogen is significantly different from other natural gas components, it influences the change in flow parameters [16]. The temperature of the inlet gas is significant in the compression process, so it was decided to adopt a value of 7°C, corresponding to the average annual temperature, according to the observation of recorded data. The starting composition of the analyzed gas was based on [17]: methane, 1% ethane and 3% nitrogen. As the proportion of hydrogen in the mixture increases, the amount of these components varies proportionally, according to equation (1).

$$x_{n_new} = x_{n_i}(1 - x_{H_2}) \quad (1)$$

where:

- x_{n_new} - molar fraction of the n-th component in the mixture at a specific H_2 fraction,
- x_{H_2} - hydrogen molar fraction in the mixture,
- x_{n_i} - initial molar fraction of the n-th component.

2. Gas compression

Increasing gas pressure, gas compressors are the main element of the gas compression station. Many of the compressors used in the natural gas transmission system are reciprocating compressors. For this reason, this work is based primarily on calculations directed to this type of compressor. Their principle is to increase the pressure due to the sliding movement of the piston in the cylinder. They can work in single- or multi-stage mode [18]. One-stage compression consists of a one-time increase in pressure in the compressor from the suction pressure to the discharge pressure. In the case of two-stage compression, the gas pressure is raised in the compressor twice, each time with a similar compression ratio. The said compression ratio expresses the quotient of the discharge pressure and suction pressure. For design work and during the selection stage of the right compressor, the choice is determined mainly by flow rates, gas composition, suction pressure and temperature, discharge pressure, structural features (for reciprocating compressors: number of cylinders, cooling, flow control) and number units [19]. In turn, the compression process itself is described by the compression ratio, isentropic or polytropic efficiency, the discharge temperature and the compression operation, which translates into the theoretical power needed to compress a specific amount of gas.

The gas compression can be described by means of a polytropic transformation in which the heat exchange with the environment occurs through the compressor construction elements. Increased heat exchange can be achieved by using cooling circuits. In calculations, the adiabatic character of the

compression is assumed, since for each compressor and the conditions in which the gas is compressed, the polytropic exponent characterizing the entire transformation is different. To estimate the error that is a simplification, the discharge temperatures were calculated according to the steps described later in this work and compared with the measured values (Table 1). In most cases, the difference between the calculated values and the measured values is about 10%. Average value is 12%.

Table 1. Comparison of the pressures measured on the compressors of the real compressor and calculated from the equations describing the adiabatic transformation. Q – flow rate, p_1 – suction pressure, p_2 – discharge pressure, T_1 – suction temperature, T_2 – discharge temperature.

Compressor No.	Sample No.	Q [m ³ /h]	Measured values				Calculated		T ₂ [°C]	Difference
			p ₁ [MPa]	p ₂ [MPa]	p ₂ /p ₁ [-]	T ₁ [°C]	T ₂ [°C]			
1	1	31345	2.21	4.70	2.12	14.00	74.00	67.53	6.47	9%
1	2	80944	3.53	4.81	1.36	17.00	43.00	38.54	4.46	10%
1	3	71186	3.27	4.89	1.50	17.00	51.00	45.18	5.82	11%
2	4	64604	3.73	4.81	1.29	9.00	32.00	26.29	5.71	18%
2	5	77107	3.06	4.90	1.60	9.00	46.00	41.45	4.55	10%
2	6	49578	2.68	4.80	1.79	15.00	63.00	56.03	6.97	11%
3	7	44955	2.02	4.75	2.36	13.30	85.20	74.64	10.56	12%
3	8	56819	2.53	4.74	1.87	13.70	69.80	57.88	11.92	17%
4	9	68258	2.88	4.75	1.65	6.00	46.00	40.36	5.64	12%
4	10	44488	2.44	4.50	1.84	16.00	62.00	59.06	2.94	5%
5	11	56904	2.67	4.80	1.80	14.00	60.00	55.19	4.81	8%
5	12	46660	2.07	3.99	1.92	14.00	65.00	60.18	4.82	7%
6	13	84767	3.22	4.74	1.47	6.00	39.00	32.24	6.76	17%
6	14	54587	2.70	4.74	1.75	18.00	66.00	57.73	8.27	13%

In order to compress the gas, the compressors must do the specific amount of work. The ratio of the work done in isentropic transformation to actual work in the current transformation under the same conditions is defined as the isentropic efficiency of the compressor η_{is} . As mentioned, in practice, the compressors are intentionally cooled to minimize the work involved. The change in the compressor can be considered as isothermal and isentropic efficiency is replaced by the isothermal efficiency of the isothermal process. For comparative purposes, it is appropriate to refer both to the polytropic process (where it is possible to supply and / or discharge heat) and to the isentropic (no heat transfer) [20]. The difference is that the polytropic process is based on the same discharge temperature as the actual transformation, while the discharge temperature of the isentropic process is different (lower) [21], as can be seen in Table 1. For polytropic process, efficiency can be determined in the same way as for isentropic and isothermal processes. It should be noted, that in the case of polytropic or isothermal processes both compressor head and compressor efficiency have to be known based on characteristics provided by compressor manufacturer in order to calculate compressor power input, whereas the isentropic process allows calculations of compressor head from the equation of state.

Knowing that the parameters of the hydrogen significantly differ from the parameters of other components of natural gas, calculation was made of the basic characteristics of the gas compression in relation to specific fraction of hydrogen in the total mixture. The adiabatic index depends strictly on the values of the heat capacities related to the isochoric c_v and isobaric c_p processes. This is expressed in formula (2). These values in turn take different values for each substance depending on the temperature. Using the set of [22] it was noted that their change can be described as a linear dependence on temperature [16]. It should be noted that hydrogen has significantly higher thermal capacities (at 10°C: 14,23 kJ·kg⁻¹·K⁻¹) in relation to the mass than the other gases studied (c_p of methane at 10°C: 2,20 kJ·kg⁻¹·K⁻¹).

$$\kappa = \frac{c_p}{c_v} \quad (2)$$

where:

$$c_p \text{ – heat capacity in isobaric transformation } \left[\frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right],$$

$$c_v \text{ – heat capacity in isochoric transformation } \left[\frac{\text{kJ}}{\text{kg} \cdot \text{K}} \right].$$

Adiabatic index is constant for a given adiabatic transformation. To calculate the discharge temperature of the gas, the formula (3) was used, based on the adiabatic transform equations:

$$T_2 = T_1 \left(r_p^{\frac{\kappa-1}{\kappa}} \right) \quad (3)$$

where:

$$T_1 \text{ – suction temperature } [^{\circ}\text{R}, \text{K}],$$

$$r_p \text{ – compression ratio, } r_p = \frac{p_2}{p_1},$$

$$p_1, p_2 \text{ – suction (1) and discharge (2) pressure [psi, Pa],}$$

$$\kappa \text{ – adiabatic index.}$$

The last of the most important parameters of each compressor is the power of the compressor. Using the formula (4), the brake horsepower (BHP) required for a single compression cycle, expressed in horsepower [21, 22], which can be brought to theoretical power of compression. Mechanical efficiency E expresses mechanical losses and pressure losses in valves and pulsation dampers (lower efficiency is usually associated with low compression ratios).

$$BHP = 0,653 \cdot Z_{ave} \left[\frac{(Q_n)(T_1)}{E \cdot \eta} \right] \left[\frac{\kappa}{\kappa-1} \right] \left[\left(\frac{p_2}{p_1} \right)^{\frac{\kappa-1}{\kappa}} - 1 \right] \quad (4)$$

where:

$$BHP \text{ – brake horsepower per stage,}$$

$$Z_{ave} \text{ – average super compressibility factor,}$$

$$Q_{G,SC} \text{ – standard flow rate } [\text{m}_n^3/\text{s}],$$

$$T_1 \text{ – suction temperature [K],}$$

$$p_1, p_2 \text{ – suction (1) and discharge (2) pressure [Pa],}$$

$$E \text{ – parasitic efficiency (for high-speed reciprocating units } 0,72 - 0,82; \text{ for low-speed reciprocating units } 0,72 - 0,85),$$

$$\eta \text{ – compression efficiency (for reciprocating compressors } 1,0),$$

$$\kappa \text{ – adiabatic index.}$$

3. Compression of natural gas and hydrogen mixture taking into account the length of gas pipeline

In addition to the use of hydrogen as an additional energy source, attention should be paid to its physicochemical parameters, which affect its transport by pipeline [17]. Having a significantly lower viscosity than the other components of natural gas, it significantly influences the rate of pressure drop caused by friction. Taking into account the turbulent nature of the flow in the rough gas pipeline, the Panhandle B (5) equation was used [23]:

$$Q_n = 108.080 \frac{1}{\mu^{0,02}} \frac{T_n}{P_n} \left[\frac{(P_1^2 - P_2^2) - E}{L d^{0,9608} T_{avg} Z_{avg}} \right]^{0,51} D^{2,53} \quad (5)$$

$$E = 0,06843 d (H_2 - H_1) \frac{P_{avg}^2}{T_{avg} Z_{avg}} \quad (6)$$

where:

- E – potential energy, Pa²
- Q_n – normal flow rate, m³/s
- μ – gas viscosity, Pa s
- T_n – normal temperature, K
- P_n – normal pressure, Pa
- P₁ – start point pressure, Pa
- P₂ – end point pressure, Pa
- L – length of pipe, m
- d – relative density of gas, dimensionless
- T_{avg} – average gas temperature, K
- Z_{avg} – super compressibility factor, dimensionless
- D – internal diameter of the gas pipeline, m
- H_{1,2} – height of the gas pipeline at the beginning (1) and end (2)
- P_{avg} – average gas pressure, Pa

By simplifying, a constant height of gas pipeline is assumed, with a potential energy value of 0 Pa². The gas temperature was assumed to be the same as in [16], i.e. 7°C, initial gas pressure 6.4 MPa, gas pipe diameter 600 mm, nominal flow 650 000 m³/h. The average flow achieved on one of the actual compressors of the compressor was 88000 m_n³/h and suction pressure 1 MPa. The mechanical efficiency of the compressor was estimated at 78%. The remaining assumptions were assumed as in [17].

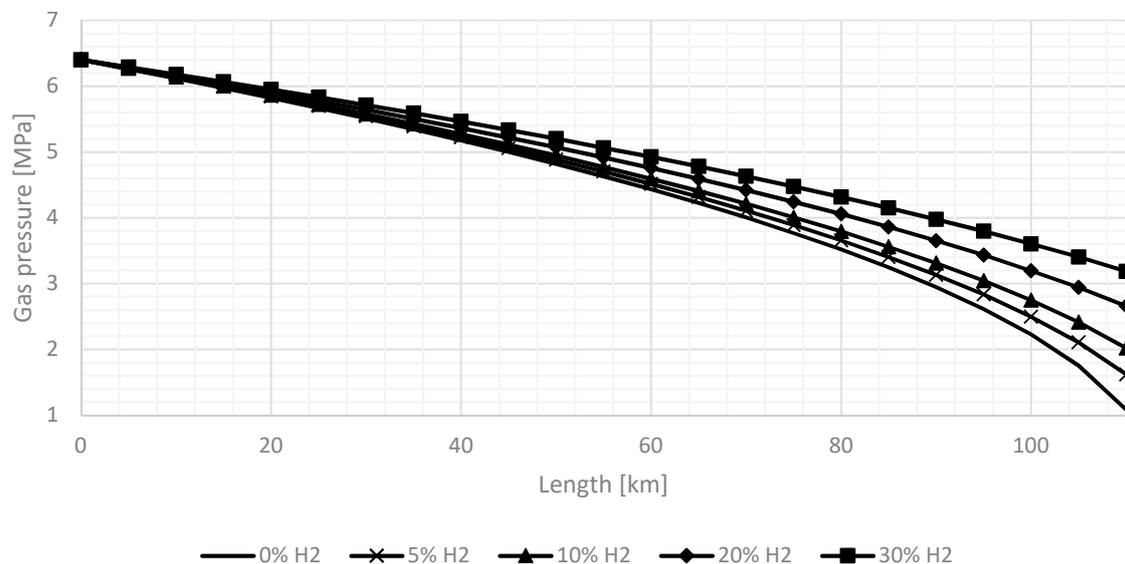


Figure 1. Gas pressure drop in a gas pipeline at a certain distance for different hydrogen fractions in a mixture with natural gas, compiled on the basis of [17].

Figure 1 shows the results of gas pressure drops in pipelines at a given distance. Figure 2 in turn represents the ratio of pressure drops obtained for mixtures with different hydrogen fractions relative to natural gas without any H₂. It is worth noting that for a 30% share of H₂ it is achieved at 110 km in this particular case, drops nearly 3 times lower than in the case of natural gas. Bearing in mind that the

potential transport of hydrogen by the transmission system would take place on the actual existing network, the impact on the work of already existing gas compression stations should be considered. The suction pressure is then equal to the gas pressure taking into account the drop caused by transport to a specific distance. As it has been shown above that hydrogen has a very positive effect on the size of these pressure drops, it was decided to refer to the compressor operating parameters obtained. Figure 3 shows the required compression ratios for gas compression stations located at different distances from the point at which the gas pressure in the gas pipeline is 6.4 MPa. Ultimately, the gas is compressed to a pressure of the same value.

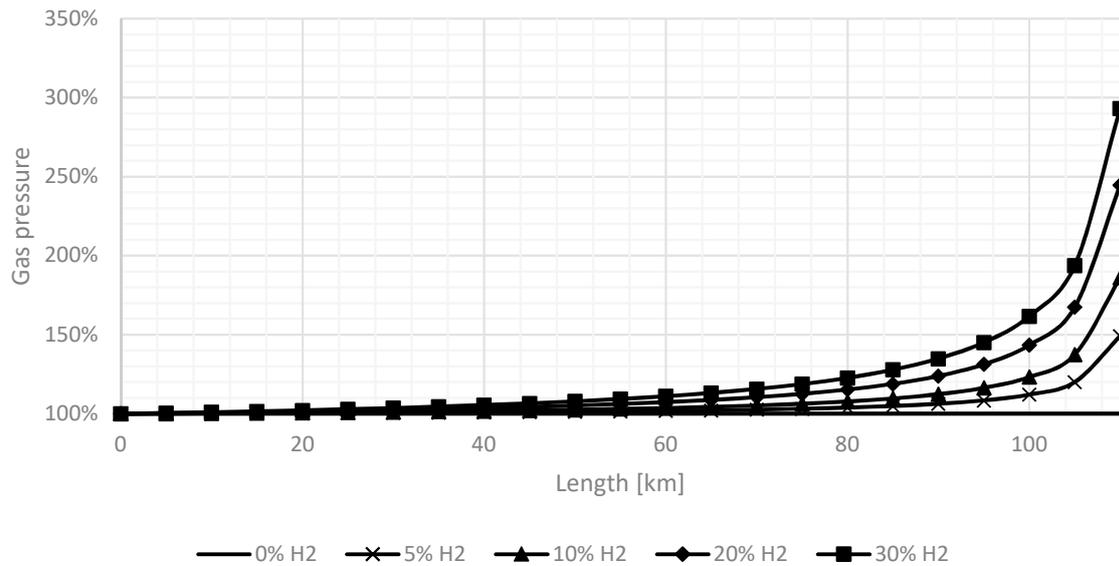


Figure 2. Gas pressure in the pipeline at a given distance for mixtures with different hydrogen fractions relative to the natural gas pressure without the addition of hydrogen.

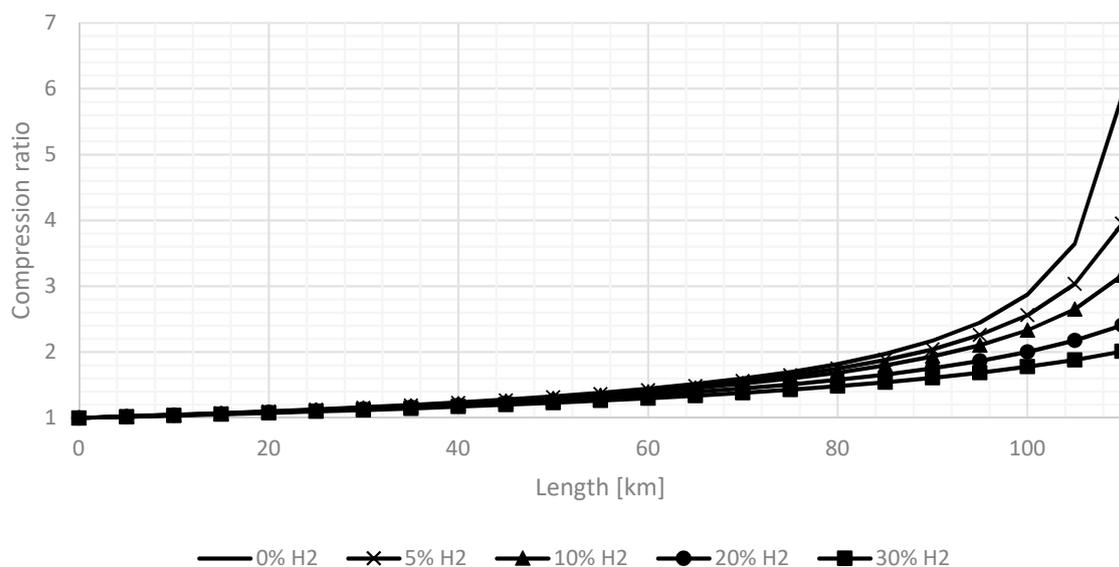


Figure 3. Required compression ratio for mixtures of natural gas with varying amounts of hydrogen depending on distance.

The greater the distance, the greater the difference between the required compression ratio for mixtures with different hydrogen proportions, as shown in Figure 4. If the gas compression station was

located at 110 km, the natural gas compression ratio without hydrogen would be close to 3 times the compression ratio for mixture of natural gas with 30% hydrogen.

Similarly, in favor of hydrogen, the calculation of the temperatures after compression is shown. While calculations have shown that the compression of a natural gas mixture with hydrogen results in a greater difference in suction and discharge temperatures than in "pure" natural gas[16], when the actual transmission of such a mixture on specific distance is taken into account, this dependence is preserved only for certain distance. In the case of a mixture with a hydrogen content of 20% and above, it does not occur, as shown in Figure 5.

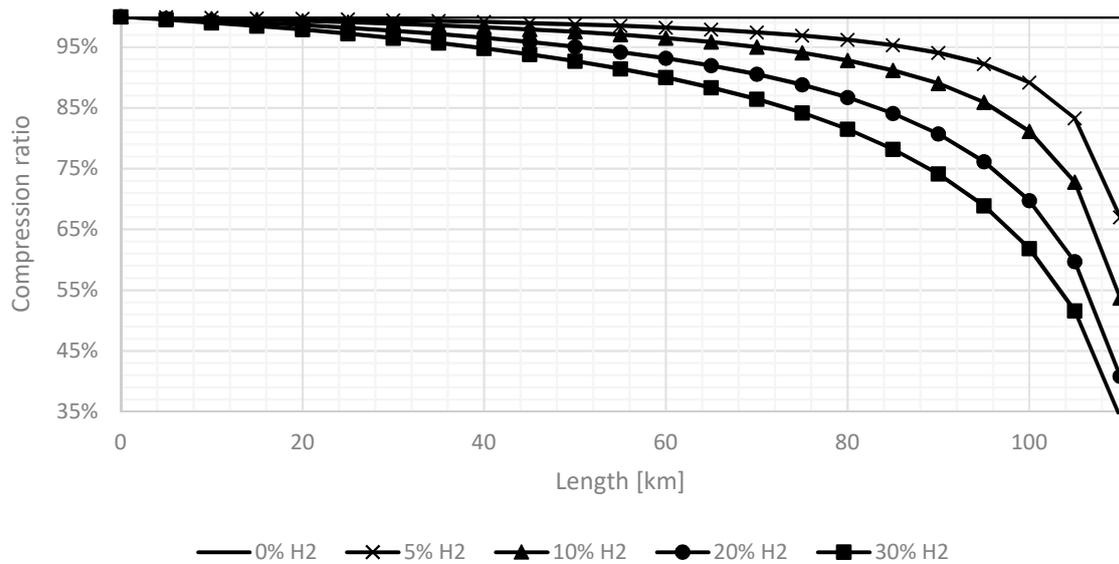


Figure 4. Required gas compression ratio at a given distance for mixtures with different hydrogen fractions relative to the required natural gas compression ratio without added hydrogen.

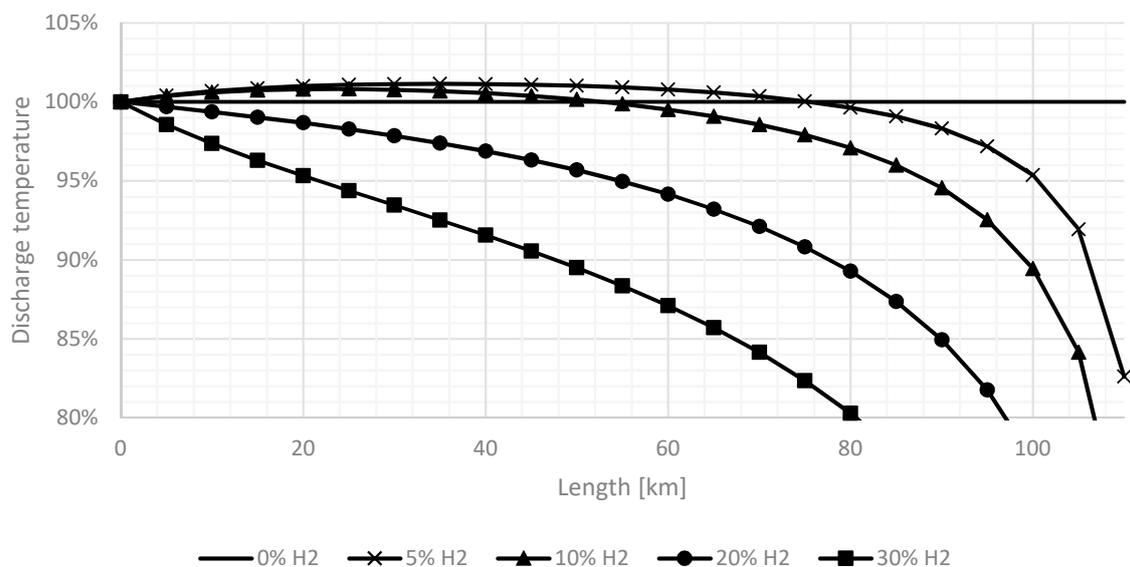


Figure 5. Ratio of discharge temperature for mixtures with different hydrogen fractions at the compression ratio required at a given pipeline distance with respect to the natural gas temperature at discharge without hydrogen addition.

The last parameter to be analyzed is the theoretical power of compression depending on the distance from the beginning of the gas pipeline. The calculation results are shown in Figure 7. Using the comparisons for the same gas compression station located at 110 km from the initial pressure point, the theoretical power required to compress the gas flowing at a rate of 88,000 m³/h equal to the values shown in Table 2. For natural gas without hydrogen, compressors of almost 8 MW are required to compress the gas from 1.5 MPa to 6.4 MPa. This is more than double that of the mixture transported to the compression station with the same gas pipeline, containing 20% hydrogen. In its case, the suction pressure is more than two times higher.

Table 2. Comparing the theoretical values of the BHP for the analyzed example.

H ₂	BHP [MW]
0%	7.88
5%	5.97
10%	4.97
15%	4.29
20%	3.78
25%	3.36
30%	3.01

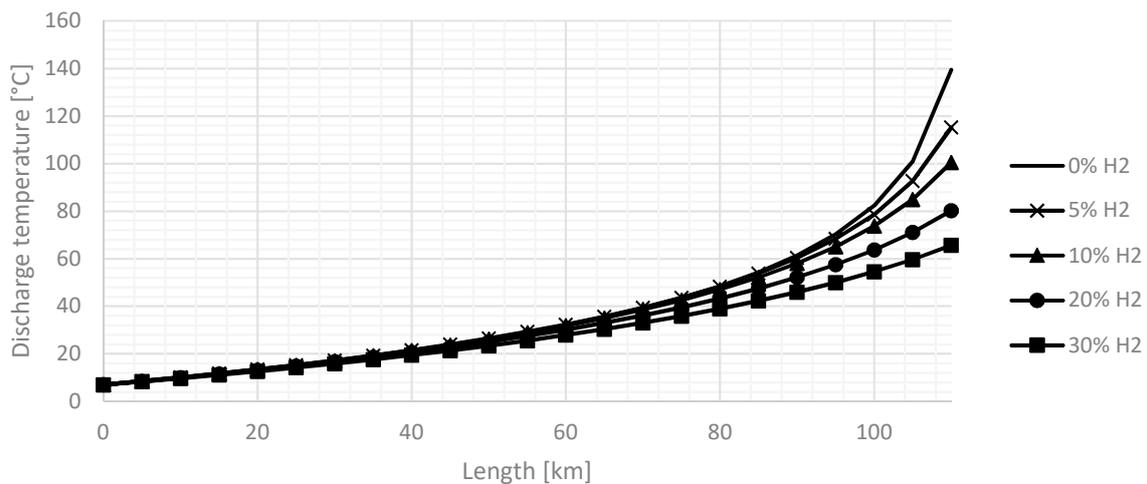


Figure 6. Discharge temperature for mixtures of different hydrogen fractions at the required compression ratio at a given distance.

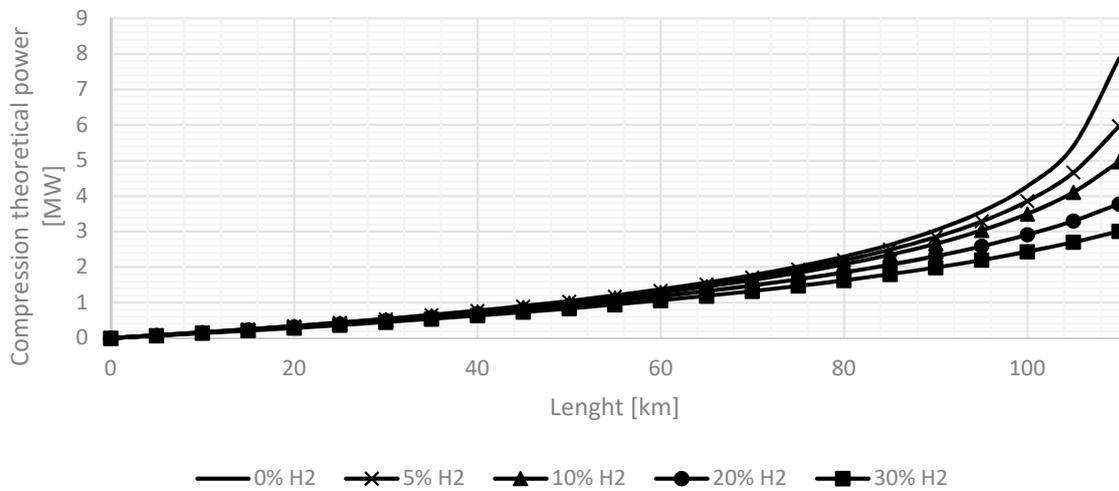


Figure 7. Theoretical gas compression power for mixtures of different hydrogen fractions at the required compression ratio at a given distance.

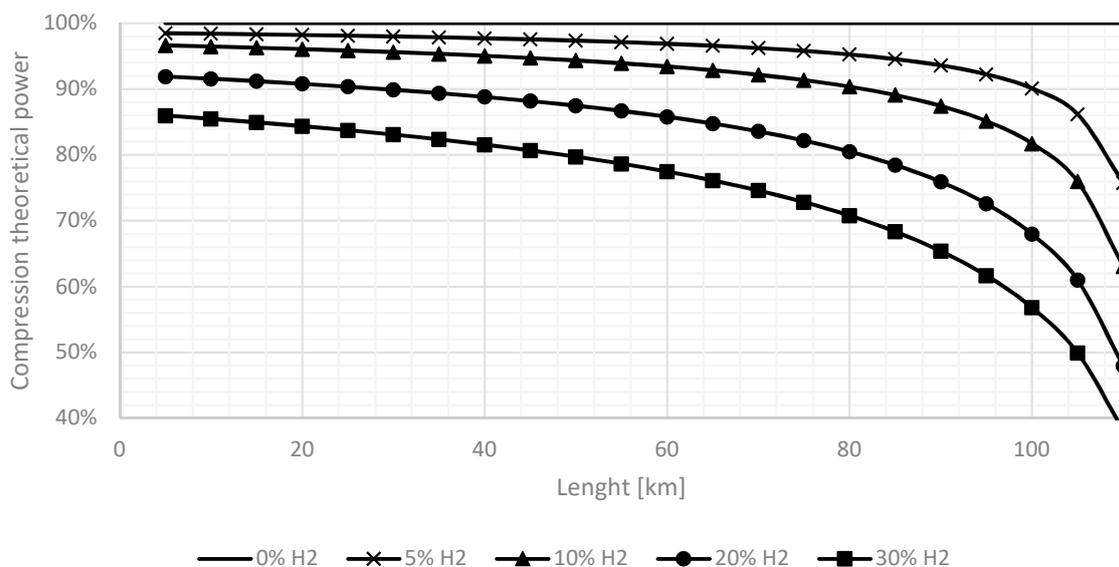


Figure 8. Theoretical compression ratio for mixtures of different hydrogen fractions at the compression ratio required at a given pipeline distance versus the theoretical natural gas compression power without hydrogen addition.

4. Summary

Differentiation of the physicochemical parameters of the hydrogen from the other components of natural gas significantly affects the nature of the gas compression process. Hydrogen has so far been paid a lot of attention for a reason. This could be confirmed by the development of the fuel cell market and the launch of new hydrogen fuelling stations. As far as research into the possibility of adding hydrogen to the natural gas transmission network has been made, it is necessary to carry out more real measurements that will provide the data needed to verify the scientific considerations.

Considering the fact that hydrogen is a gas that is much harder to compress than natural gas, the results obtained in the work permit us to say that it does not have to be an unsolvable problem. Due to the smaller friction, which in turn leads to smaller pressure losses, the transmission of natural gas with hydrogen at the same enough big distance is recorded much higher pressure than with natural gas

alone. Due to the very high influence on the temperature values after compression and the dependence of the compressor power on the compression ratio, this is of utmost importance in the whole analyzed subject. As shown in Table 3, only a small amount of hydrogen is needed to obtain significant differences in the power required on the compressors.

For the analyzed case, the addition of 5% hydrogen allowed for a higher pressure of 12% at a distance of 100 km from the starting point. This obviously results in the temperature value obtained after compression without cooling - for the compression station located at the same distance is 5% lower if there is 5% hydrogen in natural gas. However, the most important difference is the theoretical power of compression, which for such small hydrogen blends decreases by about 10%. It should be borne in mind that the calculations were subject to some simplifications. The results of the study have prompted the need for further analysis of the topic, as they may be of further benefit to the use of fuel generated by pure energy sources.

Table 3. Percentage difference of required compressor power at a given distance depending on the amount of hydrogen added to natural gas relative to natural gas without hydrogen added.

H ₂	Distance [km]								
	70	75	80	85	90	95	100	105	110
0,00%	0%	0%	0%	0%	0%	0%	0%	0%	0%
5,00%	4%	4%	5%	5%	6%	8%	10%	14%	24%
10,00%	8%	9%	10%	11%	13%	15%	18%	24%	37%
15,00%	12%	13%	15%	16%	18%	21%	26%	32%	46%
20,00%	16%	18%	19%	22%	24%	27%	32%	39%	52%
25,00%	21%	22%	24%	27%	29%	33%	38%	45%	57%
30,00%	25%	27%	29%	32%	35%	38%	43%	50%	62%

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