LEVENTE BÉLA ZUDOR

SCIENTIFIC STUDENTS' ASSOCIATION REPORT

BUDAPEST UNIVERSITY OF TECHNOLOGY AND ECONOMICS

FACULTY OF MECHANICAL ENGINEERING

DEPARTMENT OF FLUID MECHANICS

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Effect of hydrogen content on specific elements of gas transportation systems

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Budapest, 2023.

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Chapter 1

Introduction

1.1 State of the art - Green transition, role of hydrogen

Natural gas is a colorless, odorless, flammable gas mixture. In terms of its use, it can be used for heating, electricity generation, vehicle fuel and many other areas. In view of the great need and environmental awareness, a possibility arose that we could form a more favorable blend by mixing hydrogen.

Nowadays, we devote more and more attention to the protection of our environment, where possible we prefer renewable energy. However, in some areas this process is only at the beginning. This is also the case with the natural gas service industry. The heating and hot water systems of many households are still designed for fossil fuels. To help with the transition period, there are already experiments and tests on the use of the hydrogen-natural gas mixture. The dimensioning of our country's network was done for clean natural gas, and the question is what kind of interventions should be applied so that the existing system can operate safely. Of course, there is also the ideal option, according to which there is a mixture ratio that makes the current network economical and safe as well

The utility of hydrogen was recognized not only by the service provider, but also by the automotive industry. Several major automotive brands find hydrogen-based electric drive to be a longer-term solution than the more traditional battery solution. A particularly big advantage is that it can be found in almost "infinite" quantities in the atmosphere and energy only needs to be spent on its compression and storage. With this technology, the daunting disadvantage of slow "refueling" of electric cars can be solved.[44]

1.2 Natural gas systems

According to the website of Magyar Földgázszolgáltató Zrt., the natural gas supply of our country can be divided into the following units: transmission line, gas transfer station, compressor station, pipeline junction, filter-measuring station and control centers. One of the most important of these is transmission lines. Their task is to transport natural gas from domestic production sites to gas reservoirs, to the acceptance point of industrial consumers and to the national border for export purposes. According to the website, the total length of the network is 5,889 km, the length of individual lines ranges from 1 to 100 kilometers, and the diameter of the pipes is between 80 and 1,400 mm. The wires are made of high-strength steel and are protected against corrosion. Regular inspections are carried out to increase operational safety. The pressure of natural gas decreases during pipeline transport due to frictional losses. In order to maintain continuous transport and increase the transport capacity, it is necessary to increase the pressure. This task is performed by compressor stations installed at specific points of the lines. In our system, 8 locations (Beregdaróc, Nemesbikk, Hajdúszoboszló, Városföld, Csanádpalota, Szada, Báta, Mosonmagyaróvár) operate high-performance gas turbines similar to those used in airplanes to drive the centrifugal compressors that transport natural gas. It is transported at high pressure (40-75 bar) 400-700 meters under the sea. (The rotating blades of the gas compressor accelerate the transported gas, the flow speed of which in some cases approaches the speed of sound. That is why it is important to filter the natural gas before starting the pressure increase, because the liquid impurities would cause damage to the blades due to the hydraulic impact, and the solid particles would grind and wear the parts. In the diffuser following the rotating vanes, the gas is braked, and a significant part of the kinetic energy is converted into pressure energy. This is how the compressor creates the necessary gas pressure in the transmission line.) [18]

1.3 Challenges in hydrogen-NG blends

(general: pipe brittling, compressors) "The concept of blending hydrogen into natural gas pipelines is not new and has been around for decades, but there remain large knowledge gaps," said Mark Chung, NREL's hydrogen systems analysis lead. Material Solid metals can be easily permeated by hydrogen because it is the smallest element in the universe. As hydrogen atoms are absorbed and diffused within pipeline steel, they can affect the material's fatigue- and fracture-resistance properties. These impacts could render pipeline steels more susceptible to cracking. [33]

1.4 Aim of the research

The goal is to better understand the effect and flow behavior of hydrogen when mixed with natural gas. The ultimate goal is to examine the current state of the natural gas network, what risks and costs the transfer would involve, and what mixture ratio the current network is still capable of transporting. It is also necessary to examine the economy of the medium that can be transported in the present network.

1.5 Outline

This document is organized as follows. In Section 2, a brief summary on the composition and material properties of NG-H blends is provided. Section 3 explores the effect of hydrogen content on the steady-state (subsection 3.2) and unsteady (subsection 3.3) gas behavior in pipeline systems. Then, section 5 concludes the study.

Chapter 2

Natural gas - hydrogen blends

2.1 Gas mixtures

Hydrogen-enriched natural gas, or HENG, is a mixture of hydrogen and natural gas. In theory, the two can be mixed in any proportion, but typically, HENG in the range of 10 percent to 20 percent hydrogen by volume represents the most promising near-term option. At these concentrations, HENG is generally compatible with existing natural gas transmission and distribution infrastructure, as well as end-user equipment. Moreover, codes and standards in many jurisdictions treat HENG with less than 20 percent hydrogen as natural gas, which will facilitate its initial deployment into gas networks. Also, at these levels, HENG offers important emissions and potential efficiency benefits, compared with natural gas.[9]

The gas law for ideal gases can be obtained by combining three famous laws: the Boyle-Mariotte law, the Gay-Lussac law and the Charles law (see [41]).

$$PV = mRT \tag{2.1}$$

Where the $P[Pa]$ is the pressure, $V[m^3]$ is the volume, $m[kg]$ is the mass, $R_u[-]$ is the universal gas constant, $T[K]$ is the temperature. Another known form of the equation is:

$$PV = NR_uT \tag{2.2}$$

Where the $P[Pa]$ is the pressure, $V[m^3]$ is the volume, $N[mol]$ is the number of moles, $R_u[-]$ is the universal gas constant, $T[K]$ is the temperature. The total mass of a mixture of two or more gases is given by the following equation.

$$m_m = \sum_{i=1}^{k} m_i \tag{2.3}$$

The total molar mass of the mixture can be determined in the same way.

$$N_m = \sum_{i=1}^{k} N_i \tag{2.4}$$

The gas mixture can be described by specifying the $mass\ fraction\ mf_i$ or the $mole\ fraction\ y_i$ of each component i. It is important to keep in mind that

$$\sum_{i=1}^{k} mf_i = 1 \tag{2.5}$$

and

$$\sum_{i=1}^{k} y_i = 1 \tag{2.6}$$

The mole number and mass for the given component are related through the molar mass (or molecular weight).

$$m_i = N_i \mathcal{M}_i \tag{2.7}$$

To change from a mass fraction analysis to a mole fraction analysis, we can use the next formula:

$$y_i = \frac{mf_i/\mathcal{M}_i}{\sum_{i=1}^{k} mf_i/\mathcal{M}_i}. \tag{2.8}$$

$$V_i = \frac{N_i R_u T_m}{P_m} \tag{2.9}$$

and

$$V_m = \frac{N_m R_u T_m}{P_m} \tag{2.10}$$

Rearranging the quotient of the above two equations (2.9 and 2.10), we obtain:

$$vf_i = \frac{V_i}{V_m} = \frac{N_i}{N_m} = y_i \tag{2.11}$$

(2.11) shows that the volume fraction and the mole fraction of a component in an ideal gas mixture are the same.

2.2 Material properties

The agreed material properties are needed to perform the calculations. I have collected these from various sources and organized them in two tables (Table 2.1 and 2.2) below. [17] [25] [39]

Table 2.1: Hydrogen properties used in calculation

Hydrogen			
Name	Symbol	Value	Unit of Measurement
Density	ρ	0.082	kg/m^3
Isobaric specific heat	c_p	14.32	KJ/kgK
Molar mass	$\mathcal{M}$	$2.016 \cdot 10^{-3}$	kg/mol
Adiabatic exponent	κ	1.41	-
Heating value	H	10.783	MJ/m^3
Gas constant	R	4124.2	J/kgK
Mass	m	0.08	kg/m^3

Table 2.2: Natural gas properties used in calculation

Natural Gas			
Name	Symbol	Value	Unit of Measurement
Density	ρ	0.65	kg/m^3
Isobaric specific heat	c_p	2.34	KJ/kgK
Molar mass	$\mathcal{M}$	$1.9 \cdot 10^{-2}$	kg/mol
Adiabatic expander	κ	1.27	-
Heating value	H	34	MJ/m^3
Gas constant	R	518.28	J/kgK
Mass	m	0.829	kg/m^3

Based on the relationships and derivation in the previous section, we can determine the property of the mixture that is important for us.

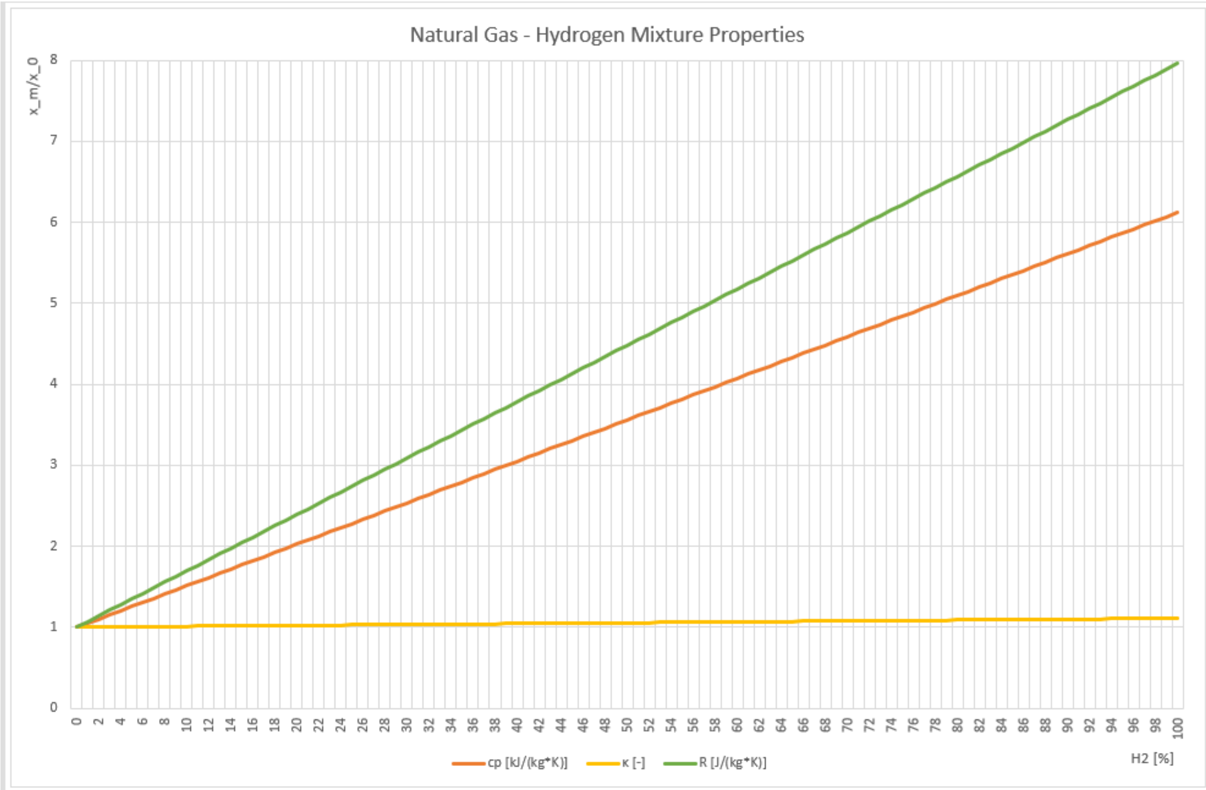

Figure 2.1: Mixing effect on the specific heat capacity, gas constant, κ.

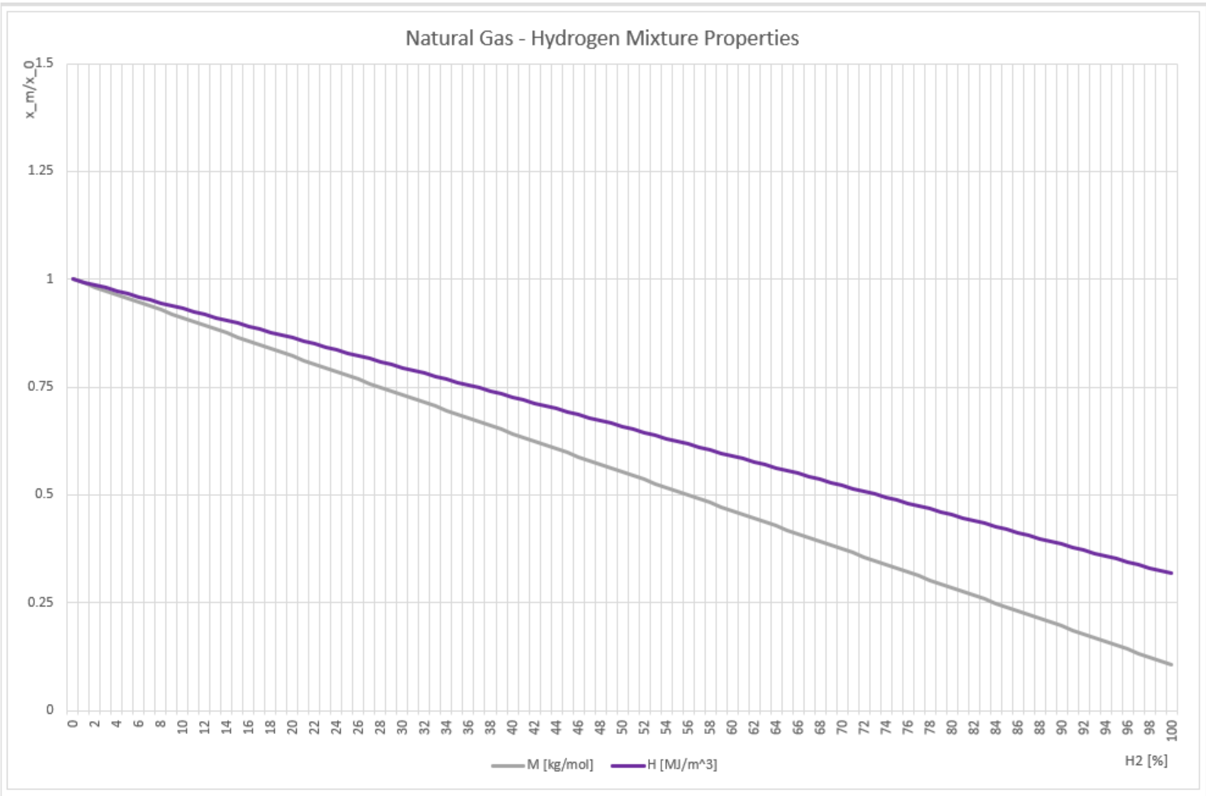

Figure 2.2: Mixing effect on the molar mass, heat capacity

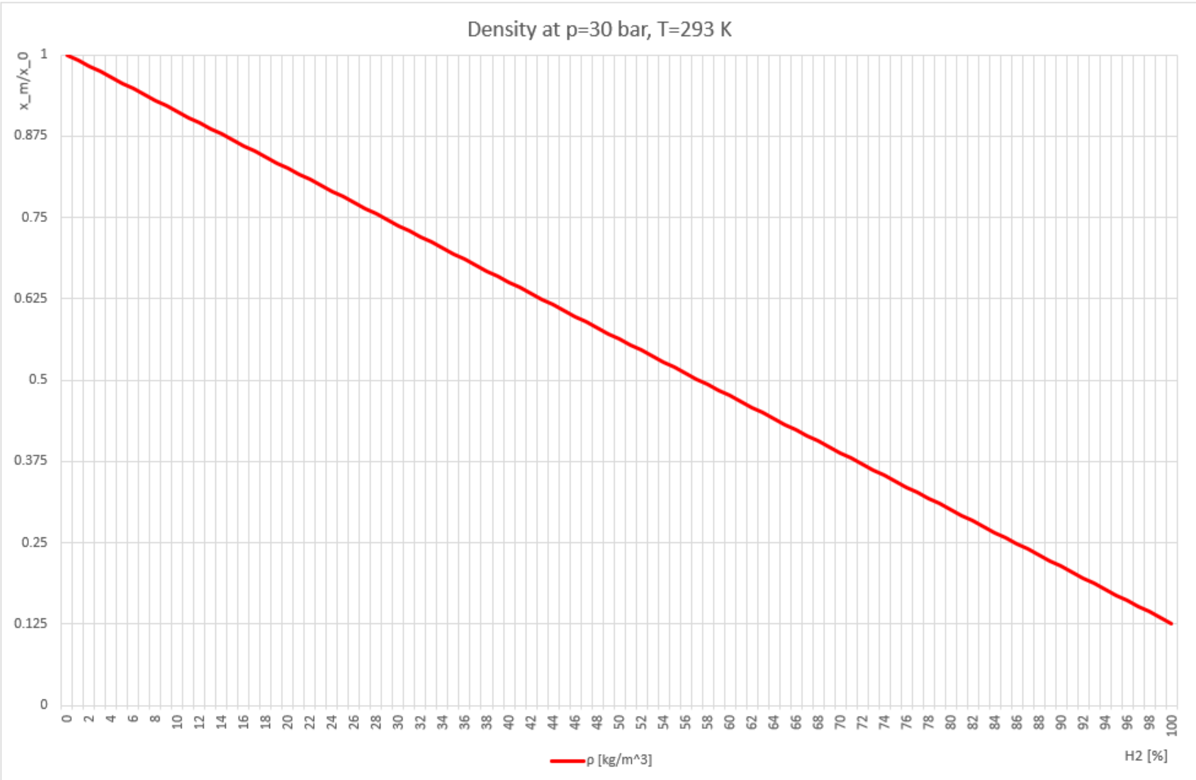

Figure 2.3: Mixing effect on the ρ.

Chapter 3

Flow in pipelines

3.1 Introduction

Pipeline systems for transporting natural gas (in the future only NG) are a vital part of the global energy infrastructure. These interconnected pipeline networks play a huge role in transporting natural gas from the fields to distribution points and end users. Known for its clean-burning properties, natural gas is used in a wide range of applications, including heating, electricity generation, industrial processes and as a transport fuel. This article provides a comprehensive overview of natural gas transmission pipeline systems, highlighting their importance, infrastructure, safety measures and future prospects.[30]

Natural gas pipelines are engineered to transport natural gas over varying distances, from local distribution to long-distance transmission. These pipelines come in different sizes, ranging from small distribution lines that serve local communities to large transmission pipelines that traverse entire regions or countries. The choice of pipeline diameter is determined by factors such as the required gas flow rate, the distance to be covered, and the pressure at which NG needs to be transported.[8]

The journey of NG in the pipeline system begins at production sites, where it is extracted from underground reservoirs. The gas is then subjected to processing to remove impurities, such as water, sulfur, and carbon dioxide, making it suitable for transportation. Once purified, the is transported through the pipeline system to various points of consumption, including residential and commercial users, power plants, and industrial facilities. This well-coordinated delivery system ensures a reliable and consistent supply of NG.

Maintaining the appropriate pressure is essential for the efficient transportation of NG through the pipeline system. Compressor stations, strategically located along the network, are responsible for regulating gas pressure and ensuring a continuous flow. These stations use powerful compressors to boost the gas pressure as it travels over long distances. Pressure regulation is critical for preventing gas flow disruptions and ensuring a steady supply. [35]

Maintaining the required pressure is essential for efficient transport of natural gas through the pipeline system. Compressor stations strategically placed along the network are responsible for controlling gas pressure and ensuring a continuous flow. These stations use powerful compressors to boost gas pressure as it travels over long distances. Pressure control is critical to preventing gas flow disruptions and ensuring a continuous supply.[35]

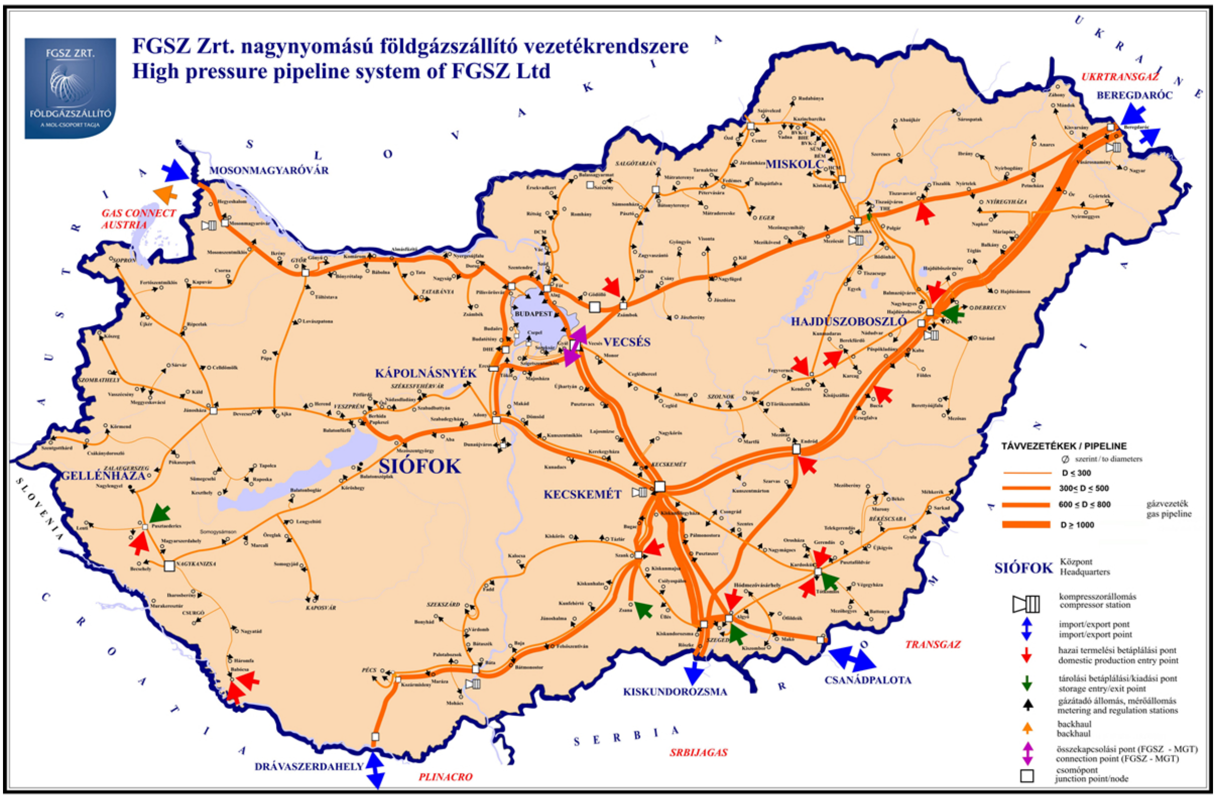

Figure 3.1: Overview of the NG transportation system of Hungary, see [1]

Pipeline systems are a particularly environmentally friendly way of transporting natural gas. Compared to alternative modes of transport such as trucking or shipping, pipelines produce fewer emissions and have a smaller carbon footprint. This makes them the preferred choice for environmentally conscious natural gas transport.

The construction of the gas pipeline infrastructure involves a large initial investment. However, pipelines, once in operation, are highly cost-effective for transporting natural gas over long distances. Lower operating costs help to keep natural gas prices competitive in the energy market. In addition, the long lifetime of pipeline systems often justifies the initial investment.

Natural gas pipeline systems are subject to strict regulations and safety standards imposed by government agencies and industry organizations. Compliance with these regulations is essential to ensure the integrity of the pipeline system and to maintain public confidence. Regular reports and audits ensure that pipeline operators adhere to safety and environmental guidelines, contributing to the overall reliability of the system.

3.2 Steady flow

3.2.1 Isotherm pipe flow with friction

Consider the flow of an ideal gas in a straight pipe of length L and diameter D, with a pipe friction coefficient λ. For long pipelines with thin pipe walls buried in the ground, one can assume constant temperature along the pipeline (due to the high heat transfer coefficient), see [42] (section 10.2.5).

The pressure drop along an axial length of dx is

$$-dp = \frac{\rho}{2} v^2 \frac{dx}{D} \lambda. \tag{3.1}$$

Let $\dot{m}$ denote the mass flow rate of the gas, hence the flow velocity is $v = \frac{\dot{m}}{\rho A}$ (A being the cross-section of the pipe). Employing the ideal gas law ($p = \rho RT$), we have

$$-dp = \frac{\rho}{2} \left(\frac{\dot{m}}{\rho A} \right)^2 \frac{dx}{D} \lambda = \frac{\dot{m}^2}{2} \frac{RT}{pA^2} \frac{\lambda}{D} dx \tag{3.2}$$

As the mass flow rate and the temperature are constant, one can rearrange and integrate both sides:

$$-\int_{p_1}^{p_2} p \, dp = \frac{\dot{m}^2}{2} \frac{RT}{A^2} \frac{\lambda}{D} \int_0^L 1 dx \tag{3.3}$$

that is

$$\frac{{p_1}^2 - {p_2}^2}{2} = \frac{\dot{m}^2}{2} \frac{RT}{A^2} \lambda \frac{L}{D} = \frac{\rho_1}{2} v_1^2 \lambda \frac{L}{D} p_1 = \Delta p'_{inc} p_1, \tag{3.4}$$

where $\Delta p'_{inc} = \lambda \frac{L}{D} \frac{\rho_1}{2} v_1^2$ stands for the pressure drop computed via assuming incompressible flow with velocity v_1 and pressure p_1 along the whole pipe.

3.2.2 *Adiabatic pipe flow with friction (Fanno flow)*

Fanno flow is the adiabatic flow through a constant area duct where the effect of friction is considered. The duct area is assumed to be constant, the flow is assumed to be steady and one-dimensional, and no mass is added within the duct. Phenomenologically speaking, the wall shear (friction) causes pressure drop, which results in a density decrease, which, in turn, accelerates the flow. For a long enough pipe, the flow can become choked, i.e. it reaches $Ma = 1$. However, this only applies for subsonic inlet flow. For a flow with an upstream Mach number greater than 1.0 in a sufficiently long duct, deceleration occurs and the flow can become choked.

Without derivation, the equation governing the Fanno flow is

$$\frac{dM^2}{M^2} = \frac{\kappa M}{1 - M^2} \left(1 + \frac{\kappa - 1}{2} M^2\right) \frac{\lambda}{D} dx \tag{3.5}$$

Figure 3.2 depict the pressure, temperature and velocity distribution in a 30-km-long pipeline, assuming Fanno flow (solid line) and isotherm pipe flow. The inlet conditions were $p_1 = 60$bar, $T_1 = 293$K and $M = 0.01$ ($v_1 = 3.43$m/s). The pipe diameter was 0.1 m, with a friction factor of $\lambda = 0.02$. It can be clearly seen that the temperature change is small (due to the low velocities), hence, from the practical point of view, there is no significant difference between the adiabatic and isotherm flow.

In the following section, we will use the isotherm approximation to explore the effect of H2 blends on the pipeline hydraulics.

3.2.3 *Change in the pipeline capacity due to blending*

In this section, we explore the effect of H2 blending on the capacity of a NG pipeline; i.e. the change of the mass flow rate and energy flux through the duct for a prescribed pressure difference. Figure 3.3 depicts the change of the pipeline capacity as a function of the H2 content, i.e. the mass flow rate through the pipe of length 1km, diameter 100mm and friction coefficient, for $p_{in} = 60$bar and $p_2 = 30$bar. The isotherm flow model was employed to provide this estimation. Moreover, we have rerun the same computation with 10km and 100km pipe lengths, but the relative change remained the same.

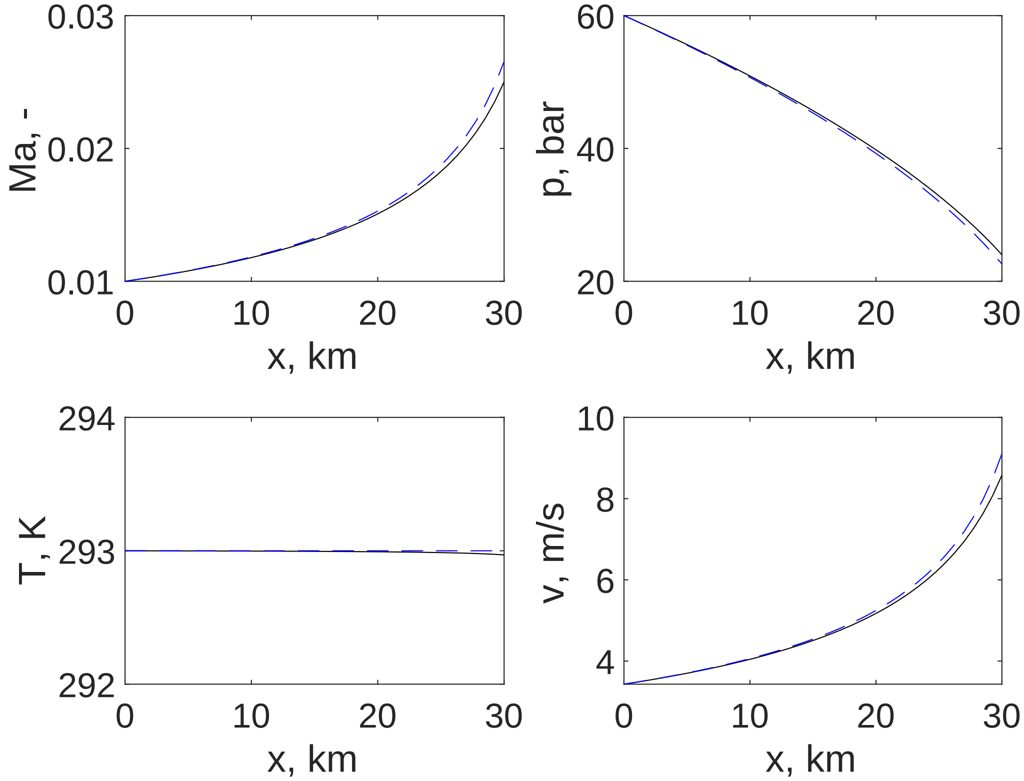

Figure 3.2: Mach number, pressure, temperature and velocity distributions along the pipe in the case of Fanno flow (solid line) and isotherm flow (dashed line).

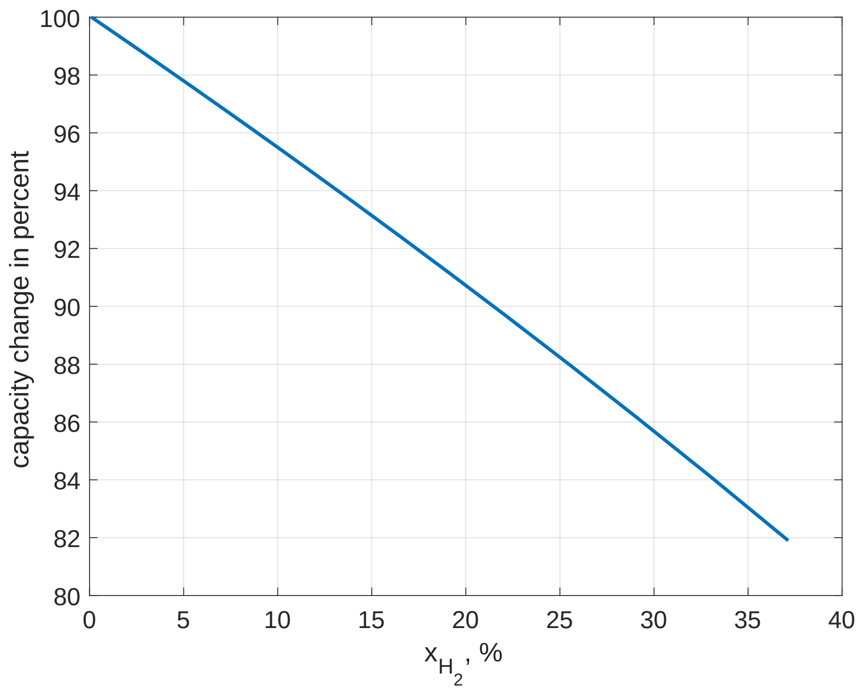

Figure 3.3: Change in the pipe mass flow rate for the same pressure drop (30 bar) in the case of a pipe of 1 km length.

Let us calculate the "energy flow " through the pipe, that is, the mass flow rate of the mixture multiplied by the heating value ($\dot{m} \times H\,(MJ/s)$) and analyze the change of this quantity.

- at $x_{H_2} = 0\%$: $\frac{\dot{m}_0}{\dot{m}_{100}} = 1$ and $\frac{\dot{H}_0}{\dot{H}_{100}} = 1$, giving 100%
- at $x_{H_2} = 10\%$: $\frac{\dot{m}_{10}}{\dot{m}_{100}} = 1$ and $\frac{\dot{H}_{10}}{\dot{H}_{100}} = 1$, giving 91%
- at $x_{H_2} = 20\%$: $\frac{\dot{m}_{20}}{\dot{m}_{100}} = 1$ and $\frac{\dot{H}_{20}}{\dot{H}_{100}} = 1$, giving 82%
- at $x_{H_2} = 30\%$: $\frac{\dot{m}_{30}}{\dot{m}_{100}} = 1$ and $\frac{\dot{H}_{30}}{\dot{H}_{100}} = 1$, giving 73%
- at $x_{H_2} = 40\%$: $\frac{\dot{m}_{40}}{\dot{m}_{100}} = 1$ and $\frac{\dot{H}_{40}}{\dot{H}_{100}} = 1$, giving 64%

The heating value of natural gas changes when hydrogen is added. The change in calorific value depends on the amount of hydrogen added. Hydrogen is the gas with the highest energy content and is often used to increase the calorific value. If hydrogen, which is a clean and flammable gas, is added to natural gas, the calorific value of the mixture can increase. However, due to the rarefaction of hydrogen, its value per mass flow rate decreases. This negative effect can be eliminated by passing the gas through the medium at a higher rate proportional to the dilution of the gas mixture.

3.3 Unsteady flow

According to Joukowsky's theory, Δv velocity change results in $\Delta p = \rho a \Delta v$ pressure change, thus, assuming the same change in velocity, the product ρa will dictate the change in the amplitude of the generated pressure wave.

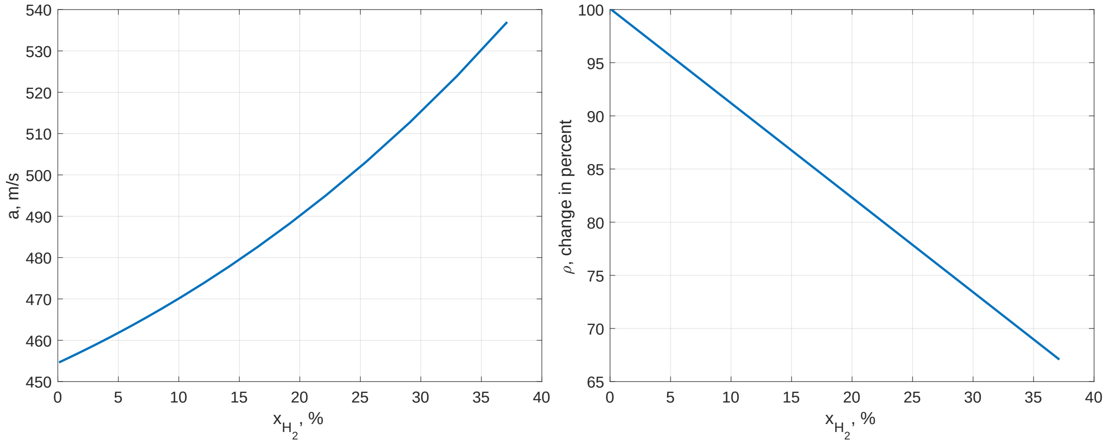

Figure 3.4: (Left) Change in the sonic velocity, (right) change in the density at $p = 60.bar, T = 293K$

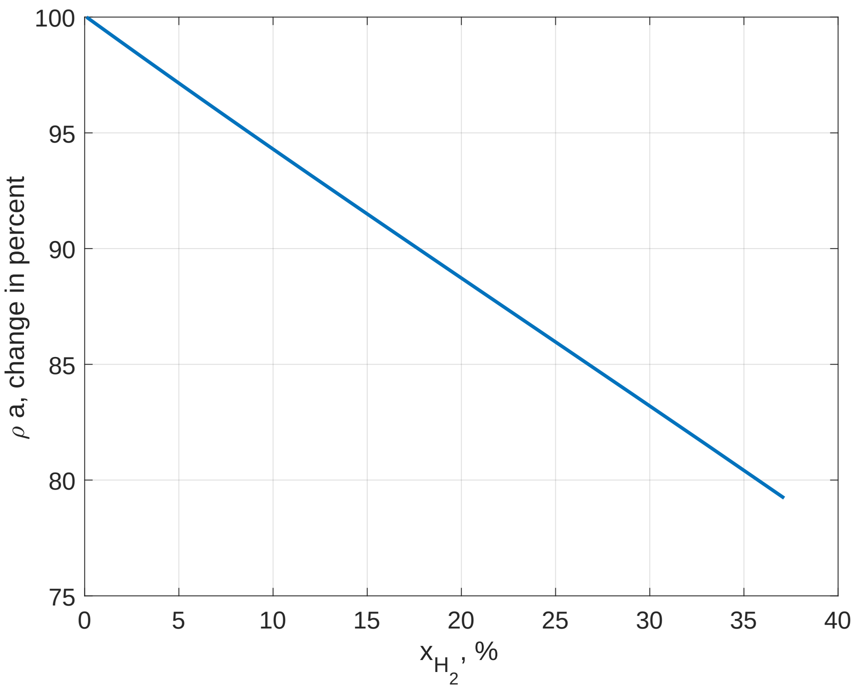

Figure 3.5: Change in ρa at $p = 60.bar, T = 293K$.

Chapter 4

Impact of hydrogen mixtures on natural gas pipeline systems/Transport units

Determining the impact of injecting hydrogen into the natural gas pipeline system is not trivial, because significantly changing the thermodynamic and transport properties of the gas mixture can pose challenges for the existing network infrastructure and end-user appliances.

Injecting hydrogen into the gas network without careful pre-planning can have negative economic, safety and reliability consequences, both at the system and natural level.

Before migration, the potential of the existing system should be assessed, and the costs and economics of the conversion of the system and its components should be considered.

4.1 Compressor(s)

In the natural gas transmission network, centrifugal compressors driven by gas turbines compress the gas transported. These units are the compressor stations. In order to ensure a continuous and constant delivery performance, it is necessary to compensate for the pressure drop during transport. The pressure drop is due to flow and pipe friction losses.

The scooping of the gas compressor accelerates the gas being transported, which in some cases can reach the speed of sound. Therefore, it is essential to filter the natural gas before starting the boosting process, as liquid impurities would cause blade damage due to hydraulic shock and solid particles could also damage (abrade, wear) the compressor elements. In the diffuser following the rotating vanes, the gas is slowed down, and a

Figure 4.1: Compressor station [19]

significant part of the kinetic energy is converted into compressive energy. This is how the compressor creates the required gas pressure in the pipeline. [19]

4.1.1 Radial/Centrifugal compressor

A centrifugal compressor is similar in design to a centrifugal fan. The rotor (impeller) is mounted on a shaft in the scroll housing. The impeller disc consists of curved blades (impeller meridian section) and in some cases a face plate. The gas enters at the front of the volute in a direction perpendicular to the axis. After the inlet manifold of the volute, baffles move the gas in the correct direction. In the rotor, the gas flow accelerates and its kinetic energy increases (the working capacity/enthalpy of the transported material increases). The gas leaves the impeller in a radial direction, the volute collects the out-flowing gas and directs it towards the pressure nozzle, which is a diffuser (a piece of pipe with an expanding cross-section), where the gas flow slows down and its kinetic energy is partially converted into potential energy (pressure increases). [20]

The compression of hydrogen with *turbo-compressors* demands a thorough analysis of the flow inside the compressor. For a given tip speed (u_2), assuming purely radial outlet, we have

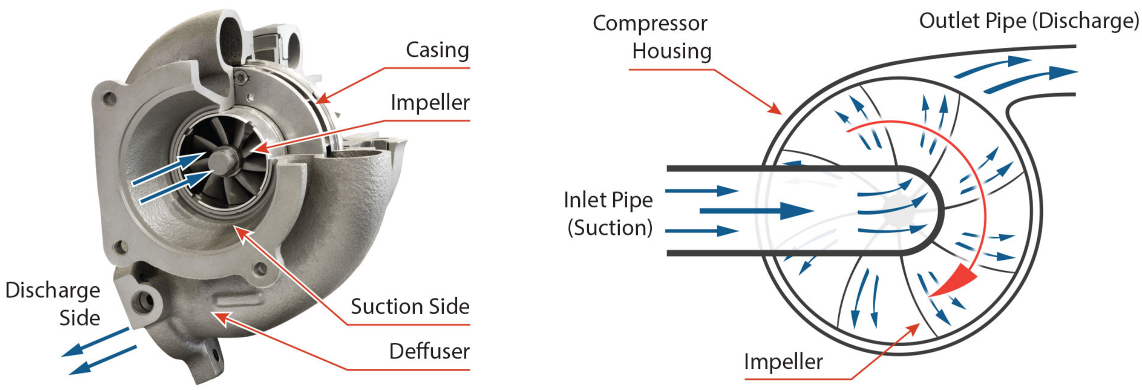

Figure 4.2: Centrifugal compressor illustration[36]

$$Y_{th} = c_{2u}u_2 = \lambda u_2, \tag{4.1}$$

where $u_2 = R_2\omega$, λ is the slip factor and Y_{th} (J/kg) is the specific work, i.e. the amount of energy added to 1 kg of substance. The slip factor can be estimated using Stodola's formula $\lambda = 1 - \pi/z$ or Stanitz's equation $\lambda = 1 - 0.63\pi/z$, for $\beta_2 = 90^o$. The total enthalpy change through the compressor change (impeller + diffuser) is

$$h_{3ts} - h_{1t} = \eta_{th}\left(h_{2t} - h_{1t}\right) = \eta_{th}\lambda u_2^2 \approx c_p\left(T_{3s} - T_1\right), \tag{4.2}$$

where T_1 is the inlet temperature, T_{3s} is the isentropic outlet temperature and c_p is the specific heat capacity measured at constant volume. Furthermore, assuming isentropic change of state, the pressure ratio of the compressor is

$$\frac{p_3}{p_1} = \left(\frac{T_{3s}}{T_1}\right)^{\frac{\kappa}{\kappa-1}} = \left(1 + (\kappa - 1)\frac{\eta_{th}\lambda u_2^2}{a_1^2}\right)^{\frac{\kappa}{\kappa-1}}. \tag{4.3}$$

This equation is extremely useful, because the compressor's pressure ratio is expressed as the tip speed u_2 (being constant for a particular compressor and revolution number) and material properties (a) inlet sonic velocity $a_1 = \sqrt{\kappa R T_1}$ and κ.

This allows us to give a brief, 'back-of-an-envelope' assumption on the theoretical case, when one tried to use a radial compressor designed for air to convey pure hydrogen. At 300 K, we have $a_{air} = 347$m/s and $a_{H_2} = 1318$m/s. Assuming $u_2 = 200$m/s and $\eta_{th} = \lambda = 1$, we have pressure ratios of

- $p_3/p_1 = 1.57$ for air, while the same compressor would provide
- $p_3/p_1 = 1.033$ (!) for hydrogen.

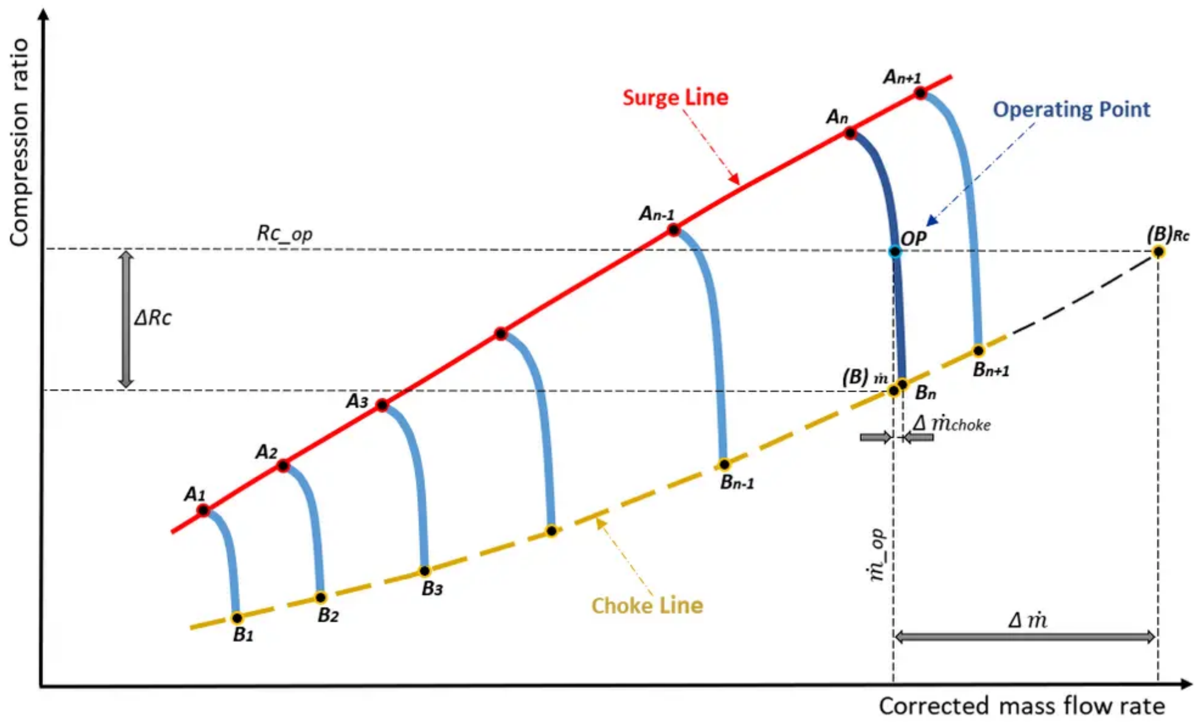

Figure 4.3: Typical performance curves of radial compressor[12]

It is worth comparing a natural gas compressor in hydrogen service also: as $\kappa_{NG} = 1.27$, $\kappa_{H_2} = 1.41$ and $R_{NG} = 518\,\text{J/kgK}$, $R_{H_2} = 4124\,\text{J/kgK}$ we conclude that the same compressor needs to rotate almost three times (!) faster to achieve the same compression ration with hydrogen as in natural gas service.[21]

Surge and choke are two potential phenomena that can affect centrifugal natural gas compressors with the addition of hydrogen, depending on design and operation. A "surge" is an unstable condition in which the flow is cyclically reversed, caused by insufficient inlet velocity. Choke or stonewalling occurs at the high flow rate end of the compressor performance curve when the velocity of the flow in the compressor reaches the speed of sound. Centrifugal compressors are characterized by a relationship between pressure rise, flow rate, efficiency and speed, often described by a performance chart that indicates conditions such as surge and choke. The composition of an unconventional gas mixture can affect the density of the inlet mixture, and thus the inlet flow rate, which can ultimately shift the compressor operation to an off-design operating condition, leading to surge or choke, depending on the compressor's springiness and operation. Variable-speed centrifugal compressors can have sufficient flexibility to avoid surge and choke conditions. According to Bainier and Kurz, a centrifugal compressor with some speed reserve can maintain a constant pressure increase by increasing speed without approaching a surge or choke condition. The maximum throughput speed is also a centrifugal compressor characteristic, which can limit the hydrogen mixing. Bainier and Kurz show examples of how the transmission rate can change with increasing hydrogen concentration. This study models off-design performance characteristics for centrifugal compressors for cases of increasing hydrogen and natural gas mixture concentrations. For the maximum volumetric flow rate, the vane speed changes little as the hydrogen fraction in the mixture increases up to 20% by volume. It is also noted that increasing the hydrogen content to 100% requires significantly more energy if the same pressure increase is to be created. Zhang et al. [22] analyzed the performance of centrifugal compressors using hydrogen mixed in natural gas pipelines and concluded that the compressor speed must be increased to maintain the energy flow. A decrease in the molecular weight (and density) of the gas mixture is the main cause of this phenomenon. Hydrogen compatibility of the compressor blade can further maximize compressor speed and affect compressor integrity. Adam, Bode and Groissboeck (2020 discuss the possibility of replacing the internal elements of the compressor with elements designed for higher hydrogen compatibility. As a note, API 617 prohibits the use of steel materials with a stress resistance greater than 827 MPa (or 120 ksi) and a hydrogen partial pressure of no more than 6.89 bar.[20]

4.1.2 *Reciprocating compressor*

Reciprocating compressors can be suitable for handling natural gas and hydrogen blends, but several factors need to be considered to ensure safe and efficient operation. When dealing with gas mixtures, especially those involving hydrogen, which is highly reactive and can lead to embrittlement of materials, it is essential to take into account the following:

Material compatibility: the materials used in the construction of the compressor and its components must be compatible with both natural gas and hydrogen. Hydrogen is known to cause hydrogen embrittlement in some materials, so it's crucial to select materials that are resistant to such embrittlement.

Safety measures: handling hydrogen requires strict safety measures due to its flammability and potential for leakage. Proper ventilation and safety systems should be in place to mitigate the risks associated with hydrogen.

Gas composition: The composition of the natural gas and hydrogen blend is important. The properties of the gas mixture, including pressure, temperature, and specific gases involved, can affect the compressor's performance and materials selection.

Lubrication: lubrication is essential for reciprocating compressors. Hydrogen can pose challenges in this regard, as it can leak through seals and potentially react with lubricants. Special hydrogen-compatible lubricants may be necessary.

Contamination and purification: Depending on the source of the natural gas and hydrogen, there may be impurities and contaminants that need to be removed or managed to prevent corrosion and damage to the compressor.

Pressure and flow rate: The design of the compressor should be suitable for the required pressure and flow rate of the gas mixture. It should be able to handle the specific requirements of the application.

Maintenance and inspection: Regular maintenance and inspection are crucial to monitor the condition of the compressor and address any issues promptly.

In the previous section, we have seen that centrifugal compressors are prone to hydrogen content in the sense that their performance (notably the pressure ratio) depends heavily on the gas composition. In the case of reciprocating compressors, the volumetric flow rate Q_s is independent of the flow rate as

$$Q_s = \eta_v n V_{st} \frac{V_s}{V_{st}} = \eta_v n V_{st} \left[1 - \frac{V_0}{V_{st}} \left(\left(\frac{p_p}{p_s} \right)^{1/n} - 1 \right) \right], \tag{4.4}$$

where η_v is the volumetric efficiency, V_{st} is the stroke volume, n is the revolution number, V_0 is the clearance (geometric data) and p_p/p_s is the pressure ratio. This means that for a given pressure ratio, revolution number and compressor geometry, the volumetric flow rate does not vary with the gas composition. Naturally, the mass flow rate $\dot{m} = \rho_s Q_s$ will vary as the density varies.

4.2 Gas turbines

Hydrogen in natural gas with higher condensation can generate abnormal phenomena in older turbines, such as excessive combustion dynamics, flashback and flameout. These phenomena occur because the addition of hydrogen to natural gas changes the flame configurations in the turbine burners. Sensitive burners can experience flame flashback, which can lead to intermittent burnout and increased carbon monoxide emissions.[3]

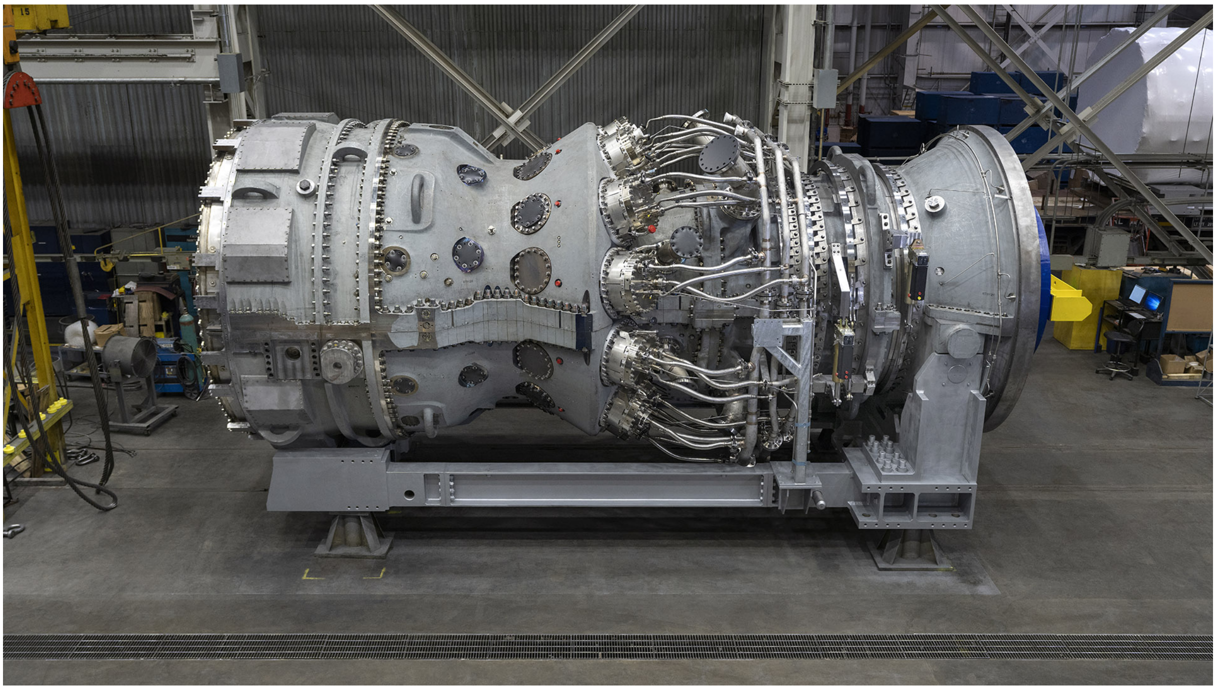

Figure 4.4: Gas turbine[3]

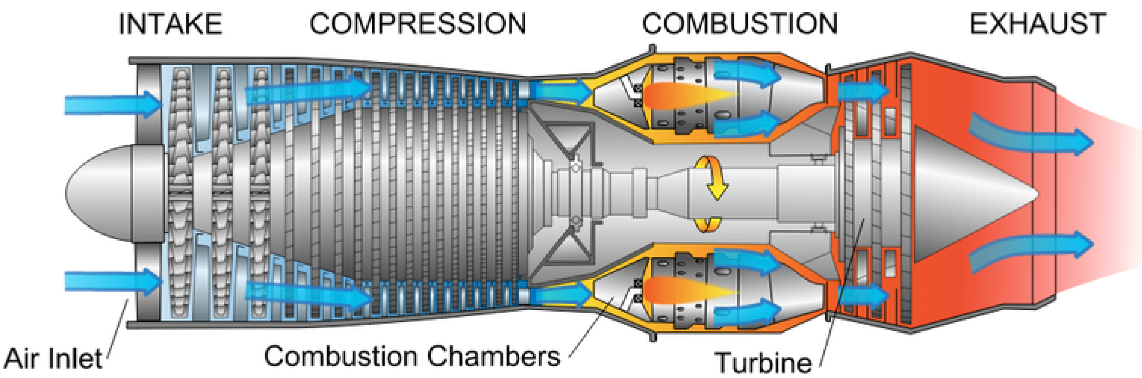

Figure 4.5: Gas turbine work illustration[4]

4.3 Valves

Figure 4.6: An Emerson Crosby safety valve.[5]

Safety valves are standard and essential elements widely used in single-phase flow applications such as gas and liquid services ([14, 7, 31]) and multiphase flow systems, e.g. nuclear plants ([32, 28]). The primary purpose of safety valves is to prevent the pressure level of a pressurized system from exceeding the maximum allowable working pressure (MAWP) by releasing overflow from the vessels and pipelines once the pressure in the system reaches the prescribed set pressure, see [27].

Safety valves operate based on the principle of pressure relief. They are designed to open and release excess pressure from a system when the pressure reaches a predetermined set point, and then close when the pressure returns to a safe level.

There are different types of safety valves, including spring-loaded safety valves (see Figure 4.6), pilot-operated safety valves, and balanced safety valves, each with its own specific operating principles and applications. The choice of safety valve type depends on the requirements of the system and the level of control and reliability needed for pressure relief.

4.3.1 *Valve capacity*

The capacity of a safety valve, often referred to as its "relief capacity" or "relief capacity rate," is a crucial specification that defines the maximum flow rate of a fluid (usually a gas or liquid) that the safety valve can discharge under specified operating conditions. It is typically expressed in terms of mass flow rate or volumetric flow rate. The capacity of a safety valve depends on several factors, including:

Set pressure: The pressure at which the safety valve opens or "pops" to release the fluid. The set pressure is usually specified in pounds per square inch (psi) or other pressure units.

Backpressure: The pressure downstream of the safety valve, which affects the capacity. The capacity decreases as backpressure increases.

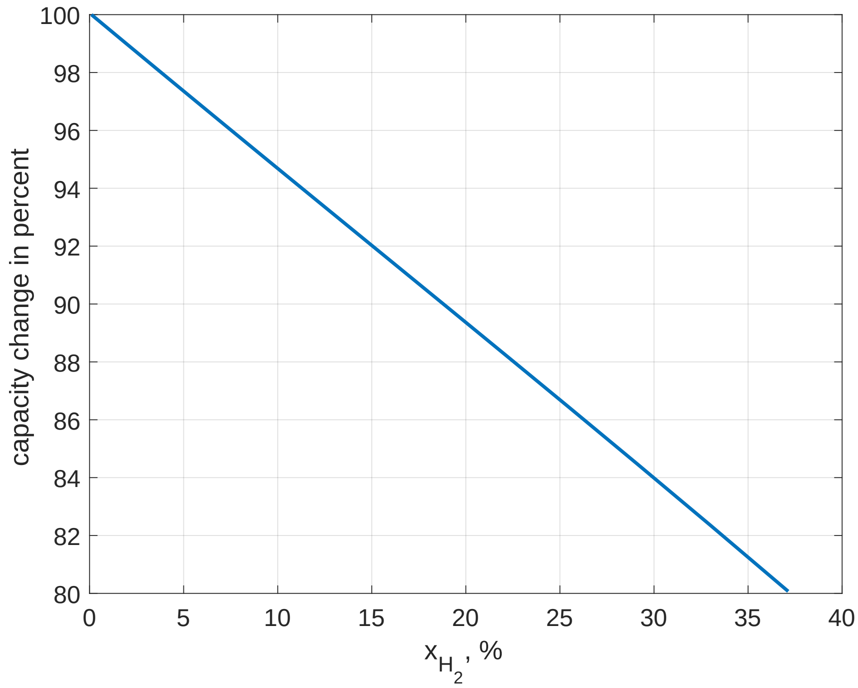

Figure 4.7: Capacity change of a relief valve as a function of the hydrogen constant.

Temperature: The temperature of the fluid can influence its density and, therefore, the capacity of the safety valve.

Fluid (mixture) properties: The properties of the fluid, such as its density, viscosity, and compressibility, can impact the valve's capacity.

Valve size: The physical size and design of the safety valve, including the orifice size and other internal features, play a role in determining its capacity.

Valve capacity is defined as the (mass) flow rate through the valve at full opening and 110% of the set pressure p_{set}. Typically, one uses isentropic relations, corrected by the C_d discharge coefficient (e.g. the API 521 standard). For isentropic choked through a nozzle of cross-section A, we have

$$\dot{m}_{th}\left(A, p_o, T_o\right) = p_o A \sqrt{\frac{\kappa \mathcal{M}}{R_u T_o}} \left(1 + \frac{\kappa - 1}{2}\right)^{\frac{\kappa+1}{-2(\kappa-1)}}, \tag{4.5}$$

and hence the capacity of the valve is

$$\dot{m}_v = C_d \dot{m}_{th}\left(A_{max}, 1.1 \times p_{set}, T_o\right), \tag{4.6}$$

where $A_{max} = D\pi x_{max}$, p_{set} is the set pressure, T_o is the upstream temperature, $\mathcal{M}$ is the molar mass and R_u is the universal gas constant.

Figure 4.7 depicts the change in the valve capacity as a function of the hydrogen content. As in the previous cases, we used (4.6) while tracking the changes in the molar mass and κ.

4.3.2 *Valve stability*

The coupling of the safety valve and pipeline wave phenomena might give rise to rich dynamics and can lead to catastrophic failure of the system, see e.g. [23] for details. Avoiding such instabilities (also known as valve chatter) requires a profound analysis of the underlying physics and dynamic prediction tools, such as in [13, 37, 38, 26]. This sizing and validating procedure becomes more complex in the case of multiphase flows, due to the changes in the fluid-structure interaction (e.g. changes in the momentum forces, mass flux) as described in [16, 10] and also because of the interphase mass transfer (i.e. flashing flow) that might occur during the relief process, see [29, 15].

The relevant codes and standards (API's [26, 27]) identify three different types of instabilities: (a) cycling, (b) valve flutter, and (c) valve chatter. The cycling stands for a valve that opens and closes multiple times during a pressure-relief event at a low frequency ($< 1Hz$) and can be caused either by valve oversizing or inlet pressure loss causing the pressure to drop transiently and the valve to shut. Once the pressure builds up again, the valve re-opens with this chain of events happening repeatedly. In contrast, flutter occurs within a high frequency self-excited periodic oscillation of the valve ($> 10Hz$), which results in an incomplete valve closure. Finally, valve chatter shows a violent fluctuation within the higher frequency that makes the valve repeatedly hits its seat. We also highlight that recently, rigorous scientific studies have identified further instability mechanisms (e.g. Helmholtz instability), which might not play an important role in most real-life applications, yet might arise under special circumstances, see [23].

The so-called quarter-wave criterion was suggested in [24] for predicting the critical pipe length in the case of single-phase application, which is

$$L_{crit} = \frac{\pi a}{2\omega_v} \frac{1}{\sqrt{2\frac{A_v p_e}{x_e s} + 1}}, \tag{4.7}$$

where $\omega_v = \sqrt{s/m}$ denotes the valve natural frequency, x_e and p_e are the equilibrium valve lift and (absolute) pressure at the valve inlet, a is the sonic velocity, s is the spring stiffness and A_v is the valve (bore) area, on which p_e acts. Beyond the critical pipe length defined by the above equation, self-excited oscillations will be born, whose dominant frequency will coincide with the pipe's first natural 'organ-mode' eigenfrequency (quarter-wave mode), $f_p = a/(4L)$. The above formula gives a straightforward way of predicting the critical pipe length. When deriving the above equation, it was also assumed that only small-amplitude oscillations arise around the equilibrium.

It is clear from (4.7) that the only parameter effected by the hydrogen content is the sonic velocity. Hence, we conclude that from the valve stability point of view, the hydrogen content slightly improves the proneness of the valve against valve chatter as the sonic velocity (and hence the maximum allowable pipe length) increases with the hydrogen content, see the left-hand side of Figure 3.4.

4.3.3 Other valve-related issues

Station valves are spaced depending on the specifications (for example, in the US, 5 to 20 miles apart) so that sections of the pipeline can be closed for maintenance . Hydrogen, the smallest molecule in the mixture, poses challenges in leak management and affects the material integrity and strength of the pipeline components. Leakage through the valve can occur in two pathways: through the valve seat and through the shaft. These leakage pathways present challenges in the containment of devices and leakage emissions.[43] Metal-to-metal technology is preferred to prevent leakage in valve seats, using a flexible and resistant metal plate that is tightly sealed on Stellite (a range of cobalt-chromium alloys designed for wear resistance) hardened valve seats. To prevent leakage downstream of the valve stem, the design of the sealing and gasket ring is important. Commonly used materials such as soft graphite are permeable to hydrogen gas and ineffective against leakage. Hard metal and precision machined seals are required to create an effective seal. O-rings made of rubber or channel packings that create multiple seals are suitable for hydrogen service below 200 degrees Celsius. It is important to note that Dutch gas transmission operator Gasunie has conducted leak and seat tests and drain operations on valves originally designed for natural gas service and found them to be safe and usable with 100 % hydrogen (Huising and Krom, 2020).[34] The brittleness-inducing effect of hydrogen also influences the valve selection criteria. Reducing the incidence of stress accumulation sites caused by sharp edges and abrupt angles during the valve manufacturing phase can mitigate this effect (a key design consideration) (Sequeira 2012). The use of electric arc welding on valves should also be avoided as the risk of stress rupture in these areas would be increased.

4.4 Distribution pipe networks

The largest part of the units responsible for the transport of natural gas are pipelines, transmission lines and their hubs. These units and networks snake underground across national borders, which is why it is of paramount importance to examine them from a material composition point of view. The pipelines transport natural gas from production sites, underground gas storage facilities and the border crossing to the point of delivery for gas distribution companies and industrial consumers. They are typically used to transport natural gas between larger geographical areas.[6] The points where lines meet are called nodes, where the connection between the lines allows the transport to be controlled to meet changing needs. At the nodes, the gas is filtered according to requirements, its quality and quantity are measured, and it is odorized on demand. The design of the pipelines to the nodes also allows for regular cleaning, maintenance and diagnostics. At each node, there is a pipeline flare through which natural gas can be extracted from the connected pipeline sections by burning it. Draining the pipelines in this way creates considerable noise and light effects due to the high pressure.[2] Natural gas distribution networks consist of steel and plastic pipes with valves, pressure regulators and metering stations. It is also necessary to investigate the behavior of the materials used by using a mixture of materials flowing through them and their elemental formula.

4.4.1 Hydrogen effects on steel tubes

According to Somerday and San Marchi, studies of steel tanks and pipelines in the industrial gas and petroleum industry show that these structures can be operated safely with hydrogen gas, although experience is limited to certain ranges of material, environmental and mechanical variables. The measured data consistently show that steels are more sensitive to hydrogen brittleness at high gas pressures. As the operating pressure is increased, higher strengths than currently used materials should be used. However, the measurements also show that steels are more sensitive to hydrogen brittleness with increasing strength. It was pointed out that the resistance to hydrogen solidification is better for steels with low manganese and silicon content. High-strength steels already exhibit significant hydrogen embrittlement in low-pressure hydrogen gas, a phenomenon not demonstrated for low-strength steels in high-pressure hydrogen gas. [40]

4.4.2 *Hydrogen effects on polymer tubes*

The effect of gaseous diffusion is to modify the mechanical properties of polymer tubes and to initiate ageing processes due to prolonged exposure to hydrogen. In-situ experiments are needed to study such effects. Very few such studies have been carried out so far in the hydrogen context. Castagnet et al. studied two semi-crystalline polymers (PE and PA11) currently used in gas distribution networks. Experimental scattering resulted from the low force levels relative to the capacity of the load cells and the frictional forces generated by the pressure equipment. However, tests on PE in atmospheric air and hydrogen at 3 MPa pressure showed negligible mechanical and hydrogen diffusion coupling. The same result held for PA11 materials, where ambient temperature dispersion appeared to be of primary importance compared to the possible hydrogen effect. "After long-term aging up to 13 months in hydrogen at various pressures (5 or 2 MPa) and temperatures below and above the glass transition of PA11 and the alpha-c transition for PE (20 °C, 50 °C and 80 °C), no deleterious effect was observed on the mechanical properties of PE and PA11. Differences observed for PA11 essentially resulted from testing temperature variability close to the glass transition temperature. Consistently with the tensile properties, no significant evolution of the crystalline microstructure after aging in hydrogen aroused from DSC experiments. Again, the clearer effect was associated with the annealing temperature in PA11." [11]

Chapter 5

Summary and conclusions

The calculation results 4.1.1 and the resulting diagrams illustrate that our current system would only be able to handle a small amount of hydrogen mixing. The volatile gas has a strong influence on the pressure response and flow rate. In order to maintain the current pressure and flow requirements, it would be necessary to use higher capacity compressors.

The stability of the valves improves slightly as the hydrogen content increases, as does the sonic velocity. Due to the small molecular size, the sealing also needs to be solved in a different way to the currently used. 4.3.3 Previous studies have already shown that metallic conductors are able to withstand the adverse effects of hydrogen. Another group of researchers has also come to the same conclusion when testing polymer (PA11) tubes. 4.4

In view of the high environmental and personal risk, many more tests and studies are needed to provide sufficient data to fully transform the networks or to make an economic assessment. Examining the existing tests for several cases and different circumstances would provide great insight and deeper knowledge.

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