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COMBUSTION PROPERTIES OF HYDROGEN-NATURAL GAS MIXTURES FROM 0 TO 100% HYDROGEN CONTENT

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Abstract: In the past few years, a rising interest has been seen in the use of hydrogen. In the long term, the aim is to replace natural gas, as it is one of the most frequently used energy sources in the EU. In the meantime, blending hydrogen into the existing natural gas pipeline network is also thought to be a promising strategy in environmental aspects. One of the most important environmental benefits of switching from natural gas to hydrogen is the decreasing amount of greenhouse gases coming from combustion. This study focuses on the changes that injecting hydrogen into the natural gas grid causes the combustion characteristics of the mentioned substances. This paper investigates whether the combustion characteristics change drastically if the volume of hydrogen varies between 0–100% or not.

Keywords: *hydrogen-natural gas blend, H_2NG, combustion characteristics, combustion properties*

1. INTRODUCTION

Hydrogen can be an energy carrier, an energy fuel and even an industrial raw material, so it is not surprising that the concept of mixing hydrogen and natural gas is not a new idea. Recent technical developments and the drive towards green energy and carbon neutrality have once again brought the topic into the centre of interest. The transport of a mixture of hydrogen and methane (the primary component of natural gas) by pipeline also has a long history (Hydrogen Europe, 2022), as pipeline networks were built for this purpose in the early 1800s. At that time, however, it was a gas mixture typically produced from coal with a hydrogen content of 30-40%, the so-called "city gas", that was used to light street lamps, commercial buildings and households. These systems served as the forerunners of today's modern natural gas networks. To reach the technical level of today's reliable networks, over the past 200 years many questions and challenges have had to be solved and answered. The next challenge for the working gas infrastructure is injecting hydrogen.

During the process of mixing hydrogen into the natural gas network, an increasing concentration of hydrogen enters the already built natural gas transport and distribution infrastructure, and gets to the end points of the system, which are the gas-using appliances. This can be done for economic or environmental reasons. The basis of the economic consideration is actually that feeding hydrogen into the already existing gas network can offer a quick and cost-effective temporary solution to the lack of immediately available dedicated hydrogen infrastructure. Furthermore, it is possible to benefit from the advantages provided by hydrogen without the burdens and obligations associated with pipeline construction. This way, mixing hydrogen also provides the possibility for users to have access to certain levels of renewable energy with low carbon dioxide emissions, which benefits corresponding to the environmental protection aspect of the mixing. (Melaina et al., 2013)

With its hydrogen strategy, the REpowerEU plan, the “Fit for 55!” climate law the European Union aims to reduce emissions by at least 55% by 2030 and save energy, diversify supplies and quickly substitute fossil fuels by accelerating Europe’s clean energy transition. All these actions make hydrogen essential to support the EU’s commitment to reach carbon neutrality by 2050 (European Commission, 2020).

Hungary’s national hydrogen strategy, published in June 2021, states that Hungary’s natural gas supply infrastructure must be prepared for the blending of at least 2 %(v/v) hydrogen. For this reason, the authors aim to point out the differences between the combustion properties and material characteristics of hydrogen and natural gas. (Hungary’s National Hydrogen Strategy, 2021) The introduction of hydrogen into natural gas distribution and transport systems can be considered as the first step on the long road to reduce the burden on our environment, thus creating an opportunity for users to burn the hydrogen-enriched gas mixture. The higher the proportion of the latter component present in the natural gas-hydrogen gas mixture, the lower the number of harmful emissions produced during combustion (Topolski et al., 2022).

2. FLUE GAS COMPOSITION OF NATURAL GAS AND HYDROGEN

The combustion process can be considered perfect if the fuel that reacts with oxygen burns completely during the reaction. The success of the process depends on whether an adequate amount of oxygen is available during combustion or not. If it is given, the reaction results in the formation of a specific amount of combustion products. *Table 1* contains the quantity values of the components of the average natural gas used for our calculations.

Table 2 shows the combustion properties of the individual components of the natural gas-hydrogen mixture (H_2NG). It can be used to compare the products produced during the combustion of hydrogen and methane. The products of perfect and imperfect combustion must be differentiated as well.

The main components of natural gas are hydrocarbons. The perfect combustion of these compounds results in carbon dioxide (CO_2) and water vapor (H_2O) formation. CO_2 has a strong greenhouse effect, so it is an undesired flue gas component, but H_2O can be considered harmless for both the human body and the environment. However, natural gas does not only contain hydrocarbons, and air does not only consist of oxygen, so it is also important to mention what happens when other compounds are also present during combustion, or more specifically the elements that make up the compounds, are burned.

Table 1

National weighted average natural gas component values used for calculations

Source: Order of natural gas quality accounting 2024–2025

Components	Formula	mol%
Methane	CH_4	92.883
Ethane	C_2H_6	3.419
Propane	C_3H_8	1.039
i-Butane	$i\text{-}C_4H_{10}$	0.179
n-Butane	$n\text{-}C_4H_{10}$	0.194
i-Pentane	$i\text{-}C_5H_{12}$	0.043
n-Pentane	$n\text{-}C_5H_{12}$	0.033
n-Hexane	$n\text{-}C_6H_{14}$	0.019
n-Heptane	$n\text{-}C_7H_{16}$	0.014
n-Octane	$n\text{-}C_8H_{18}$	0.007
Carbon-dioxide	CO_2	1.308
Nitrogen	N_2	0.862

Table 2

Combustion equations of individual components of the natural gas-hydrogen mixture

(Vida, 1991)

Main components of the natural gas-hydrogen mixture	
Hydrogen	**Methane**
Stoichiometric combustion equations	
$2\ H_2 + O_2 = 2\ H_2O$	$CH_4 + 2\ O_2 = CO_2 + 2\ H_2O$
Products of complete combustion	**Products of complete combustion**
Water	Carbon-dioxide Water
Products of incomplete combustion	
Hydrogen Nitrogen oxides	Carbon monoxide Sulfur dioxide Nitrogen oxides Residual hydrocarbons

There are some sulfur-containing compounds that can occur as trace components in natural gas. Due to the fact that there is sulfur in the combustion process, an inert gas, sulfur dioxide (SO_2), is produced, which is indirectly responsible for the formation of sulfuric acid (H_2SO_4). The most common sulfur-containing component is hydrogen sulfide (H_2S) (Vida, 1991).

Nitrogen molecules (N_2) can also be present in trace amounts in natural gas and make up more than 2/3 of the air. These molecules are also present during the combustion process, but do not directly participate in it. However, if the flame temperature is high enough, the N_2 molecules combine with the oxygen in the air and produce nitrogen oxides (NO_x) of various compositions. They can be linked to global warming as they are indirect greenhouse gases. In addition, they contribute significantly to the formation of acid rain.

In practice, absolutely perfect combustion is never achieved, so the consequences of incomplete combustion must also be taken into consideration. In the case of incomplete combustion, there is not enough oxygen during combustion for the fuel and oxygen to fully react, or something, such as a solid surface, takes the heat away from the combustion process. These cases can be summarized as improperly directed firing processes. And the potential source of danger lies in the fact that during these processes, unwanted products are produced, such as carbon monoxide (CO), nitrogen oxides (NO_x) or hydrocarbons (Vida, 1991).

During the combustion of hydrogen, as shown in *Table 1*, neither carbon nor sulfur-based combustion products are produced. The forming water vapor and residual hydrogen are harmless substances, but the nitrogen oxides (NO_x), that are also produced during the combustion of hydrogen, can cause a bigger problem, as these are strong greenhouse gases. As explained in a few paragraphs above, a sufficiently high flame temperature is necessary for NO_x to form. During the burning of hydrogen, the flame speed (which is several times higher than the flame speed that can be measured during the combustion of methane) locally raises the flame temperature to such an extent, that a sufficiently high temperature can be formed for the process to take place. With the help of a special burner, the flame temperature can be reduced, thus preventing the possibility of NO_x formation (Menzies, 2019).

Therefore, to ensure that there are no substances harmful to the environment among the products created during the burning of hydrogen, it is necessary to control the flame temperature, for example with the help of a diffusion burner. This already appears as a requirement if hydrogen is blended with natural gas, since the optimal combustion properties can only be achieved this way.

Additional criteria and critical points for mixing hydrogen into the natural gas transmission and distribution network arise from the different properties of hydrogen and methane (natural gas). Maintaining safety while blending hydrogen into the currently functioning natural gas infrastructure is not simple, because the grid is calibrated for 100% natural gas. Consequently, material grades, fittings, leak-detecting equipment and all other technologies are selected according to the composition of natural gas. It is therefore crucial to investigate how the physical and chemical properties of the gas mixture change when hydrogen is injected.

2.1. Basic differences in gas properties

Hydrogen is a diatomic molecule, so a pair of hydrogen forms unity, while methane, which is considered the main component of natural gas, has 4 hydrogen atoms attached to one carbon atom. Hydrogen is the very first element in the periodic table, and therefore it is the element with the lowest relative atomic mass. Carbon, on the other hand, occupies sixth place in the system, which means that it is characterized by a bigger relative atomic mass. Thus, while pure hydrogen has two atoms with a very low relative atomic mass, methane is a molecule with a much higher relative atomic mass and physical size. These differences foreshadow the challenges of blending hydrogen into the natural gas grid. The following paragraphs describe the combustion characteristics of the natural gas-hydrogen mixture, namely as a function of the hydrogen content. Different formulas are used to calculate the properties of H_2NG blends from 0 to 100% hydrogen content. All the formulas in this study are taken from the book of Meszléry (1978).

3. COMBUSTION PROPERTIES OF NATURAL GAS AND HYDROGEN

The energy found in natural gas, hydrogen and all in their mixtures can be released by combustion. To characterize the combustion process, stoichiometric equations are used, which are based on the consistency of the atomic number and refer to unit mass, volume or mole.

The general stoichiometric combustion equation that can be written down for the combustible components in hydrocarbons is the following

$$C_nH_m + \left(n + \frac{m}{4}\right) * O_2 = n * CO_2 + \frac{m}{2} * H_2O \tag{1}$$

where n is the number of carbon atoms [–], m is the number of hydrogen atoms [–]. *Equation 1* can be used for all the hydrocarbons that can be found in the different types of natural gases. As a result, the combustion equations of the individual components of the natural gas-hydrogen mixture are given, as can be seen in *Table 3*.

Table 3

Combustion equations of individual components of the natural gas-hydrogen mixture

(Vida, 1991)

Hydrocarbons and other components (general formula)	Stoichiometric combustion equations		Hydrocarbons and other components (general formula)	Stoichiometric combustion equations	
Methane	CH_4+2O_2	$=CO_2+2H_2O$	Heptane	$C_7H_{16}+11O_2$	$=7CO_2+8H_2O$
Ethane	$C_2H_6+3{,}5O_2$	$=2CO_2+3H_2O$	Octane	$C_8H_{18}+12{,}5O_2$	$=8CO_2+9H_2O$
Propane	$C_3H_8+5O_2$	$=3CO_2+4H_2O$	Carbon-monoxide	$CO+0{,}5O_2$	$=CO_2$
Butane	$C_4H_{10}+6{,}5O_2$	$=4CO_2+5H_2O$	Hydrogen	$H_2+0{,}5O_2$	$=H_2O$
Pentane	$C_5H_{12}+8O_2$	$=5CO_2+6H_2O$	Hydrogen-sulphide	$H_2S+1{,}5O_2$	$=SO_2+H_2O$
Hexane	$C_6H_{14}+9{,}5O_2$	$=6CO_2+7H_2O$			

3.1. Specific theoretical oxygen demand for perfect combustion

The individual stochiometric combustion equations can be combined to calculate the specific theoretical oxygen demand of the perfect combustion process. Being aware of this value is important for the calculation of the stoichiometric air-fuel ratio, that ensures efficient and complete combustion, thus fuel waste is minimized as energy output is maximized if the ratio is known. The specific theoretical oxygen demand of the perfect combustion can be written as follows

$$V_{O_2 theoretical} = 2 * r_{CH_4} + 3{,}5 * \ r_{C_2H_6} + 5 * \ r_{C_3H_8} + 6{,}5 * r_{C_4H_{10}} + \\ + 8 * r_{C_5H_{12}} + 9{,}5 * r_{C_6H_{14}} 11 * r_{C_7H_{16}} \ 12{,}5 * r_{C_8H_{18}} + 0{,}5 * r_{H_2} + \\ +0{,}5 * r_{CO} + 1{,}5 * r_{H_2S} - r_{O_2} \ \left[{m^3}/{m^3}\right] \tag{2}$$

where r_i is the volume ratio of given gas components [–].

When natural gas is burned perfectly, 2.082 m^3/m^3 of oxygen must be available, as is shown in *Table 4*. The introduction of hydrogen into the system reduces this value to a quarter, since only 0.5 m^3/m^3 of oxygen is enough for the perfect combustion of hydrogen. Therefore, the higher the hydrogen feed, the fewer oxygen molecules are sufficient for perfect combustion. Although, it is also necessary to consider that to release the same energy content in the gas appliance that is given when natural gas is burned, several times the volume of hydrogen is required, and thus several times the amount of combustion air.

Table 4

Specific theoretical oxygen demand of the H_2NG mixture for hydrogen at 20 and 100% vol

Specific theoretical oxygen demand of mixture ($V_{O_{2,theoretical}}$) [m^3/m^3]		
NG 100%(v/v)	H_2NG 20%(v/v) H_2	H_2 100%(v/v)
2.082	1.766	0.500

Considering the financial aspects of mixing, it is important to define the concentration limit below which the related gas-using equipment does not even have to be modified or replaced under certain conditions. Several studies have addressed the issue, the consensus of these is that the general limit of mixing hydrogen and natural gas is at 20%(v/v), adding that this is a theoretical maximum. (Lévai and Laza, 2024; Birkitt et al., 2021) It can be said that below 20%(v/v), the change in properties is so small that there is no need to modify the most critical points of the system, the gas-using appliances. For this reason, the values for specific theoretical oxygen demand and other calculations are shown for 0, 20 and 100%(v/v) H_2 content.

3.2. Specific theoretical air requirement for perfect combustion

Based on the fact that approximately 21% is the oxygen content of the air, the formula for the specific theoretical air requirement for perfect combustion is given in *Equation 3*

$$V_{air_{theoretical}} = \frac{100}{21} * V_{O_2\,theoretical} \left[{m^3}/{m^3}\right] \tag{3}$$

The specific theoretical air requirement defines the exact amount of air needed to completely oxidize the fuel, leading to complete combustion this way. Knowing the specific theoretical air requirement is essential for designing safe, efficient, and clean combustion systems.

Table 5

Specific theoretical air requirement of the H_2NG mixture for hydrogen at 20 and 100% vol

Specific theoretical air requirement of a mixture ($V_{air_{theoretical}}$) [m³/m³]		
NG 100 v/v%	H_2NG 20 v/v% H2	H_2 100 v/v%
9.916	8.409	2.381

When natural gas is burned perfectly, an air volume of 9.916 m^3/m^3 must be available, as shown in *Table 6*. The introduction of hydrogen into the system reduces this value by almost a quarter, since only 2.381 m^3/m^3 of air is enough for the perfect combustion of hydrogen. Therefore, the higher the hydrogen feed-in, the less air is sufficient for perfect combustion to occur. This confirms what has been discussed in the previous paragraph.

3.3. Specific volume of flue gas components

The amount of flue gas produced during perfect combustion decreases continuously in proportion to the increase in hydrogen content, since the amount of specific oxygen required to burn a unit of hydrogen is significantly less than in the case of natural gas. Therefore, the number of individual components of the flue gas is also continuously decreasing, as can be seen in *Figure 1*.

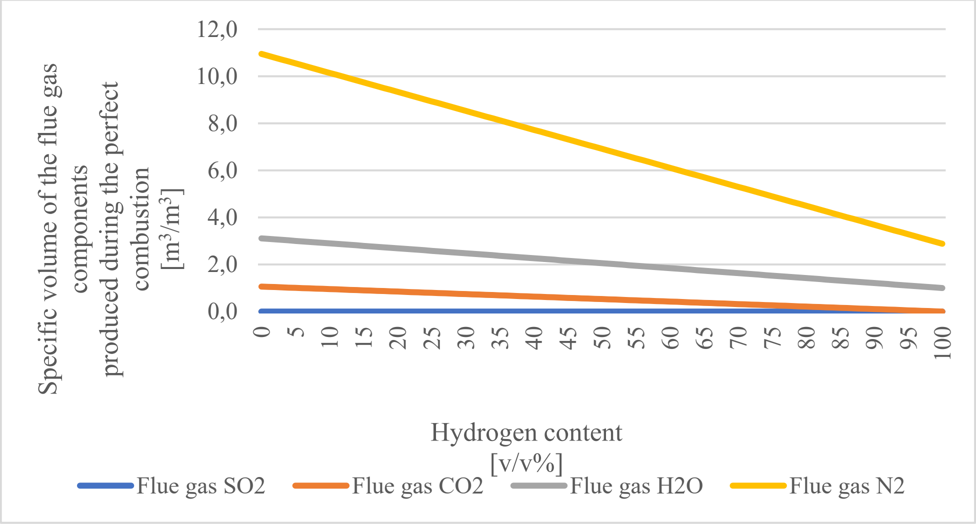

Figure 1

The effect of hydrogen feed on the specific volume of the flue gas components produced during the perfect combustion of the H_2NG mixture

3.4. Flammability concentration limits

To ensure the safe use of the hydrogen-natural gas mixture, it is essential to understand the explosion hazards associated with these mixed gaseous fuels. The flammability concentration limit – also known as the explosion limit – is commonly used as a key indicator in the quantitative risk assessment of explosion risks related to these fuels. There are two types of flammability limits, the Lower Flammability Limit (LFL) and the Upper Flammability Limit (UFL), which define the leanest and richest fuel-air mixtures capable of sustaining combustion. (Jiao et al., 2019) The limits of the range are influenced by many factors, including initial temperature, pressure, quantity and quality of contaminants, ignition source, etc. The addition of inert gas (non-combustible, e.g. N_2, CO_2) significantly affects only the upper concentration limit by decreasing it. Therefore, injecting more inert gas narrows the ignition range. The ignition concentration limits of gas mixtures can be calculated using the Le Chatelier equation, shown in *Equation 4, 5* and *6*

$$Z_{blend} = Z_{c_{blend}} \frac{1 + \frac{B}{1-B}}{1 + Z_{c_{blend}} * \frac{B}{1-B}} \left[{}^{m^3}/_{m^3}\right] \tag{4}$$

$$Z_{c_{blend}} = \frac{1}{\sum_{i=1}^{n} \frac{x_{ci}}{Z_{ci}}} \left[{}^{m^3}/_{m^3}\right] \tag{5}$$

$$x_{ci} = r_i * \frac{1}{1-B} \; [-] \tag{6}$$

where Z_{blend} is the upper or lower ignition concentration limit for each component [m^3/m^3], $Z_{c_{blend}}$ is the lower or upper ignition concentration limit of the mixture calculated on the combustible part [m^3/m^3], x_{ci} is the volume ratio of combustible component to combustible material in the mixture [–], B is the inert content of the mixture [–], Z_{ci} is the upper or lower ignition concentration limit for each combustible component [m^3/m^3].

3.5. Inert content of the gas mixture

The inert content of the natural gas-hydrogen blend shows the summary of the proportions of non-combustible components in the gas mixture, as shown in *Equation 7*

$$B = \sum_{i=1}^{n} x_i \; [-] \tag{7}$$

where x_i is volume fraction of non-combustible components of the gas mixture [–].

Our calculations led to the result, that the value of the inert content decreases to zero because of hydrogen injection, since hydrogen is a combustible component. Therefore, increasing the hydrogen content cannot increase the proportion of non-combustible components (CO_2, N_2 and O_2 content). This conclusion is supported by the calculation results in *Table 6*.

Table 6

Inert content of the H_2NG mixture for hydrogen at 0, 20 and 100%(v/v)

Inert content of mixture (B) [-]		
NG 100%(v/v)	H_2NG 20%(v/v) H2	H_2 100%(v/v)
0.010	0.008	0.000

3.6. Volume quotient of combustible components

For further calculations, it is necessary to calculate the volume quotient of combustible components *(Equation 8)*, to establish the flammability concentration limits for the combustible material and then for the whole mixture.

$$x_{ci} = x_i * \frac{1}{1-B} \; [-] \tag{8}$$

where x_i is the volume fraction of combustible components of the gas mixture [–], B inert content of the mixture [–].

Under the influence of hydrogen feed, practically the volume ratio of all components (other than hydrogen) decreases linearly until it reaches zero as the proportion of hydrogen increases from 0 to 100%(v/v).

3.7. Lower flammability limit of the gas mixture

The first step of calculating the flammability concentration limits is calculating the flammability limits of the combustible content of the hydrogen-natural gas mixture. The lower flammability limit (LFL) refers to the minimum concentration of a combustible component in a gas mixture that can support flame propagation in the presence of an ignition source. Below this concentration, the mixture is too lean to ignite or sustain combustion. (Jiao et al., 2019) The lower flammability limit for the concentration of the combustible content of the gas mixture can be calculated by *Equation 9*

$$Z_{c_{blend_{lower}}} = \frac{1}{\sum_{i=1}^{n} \frac{x_{ci}}{Z_{c_{lower\,i}}}} \left[{}^{m^3}/_{m^3} \right] \tag{9}$$

where x_{ci} is the volume ratio of combustible component to combustible material in the mixture [–], $Z_{c_{lower\,i}}$ is the lower flammability concentration limit for each combustible component [m^3/m^3].

Table 7

Lower flammability limit of the combustible content of H_2NG mixture for hydrogen at 0, 20 and 100%(v/v)

Lower limit of flammability concentration of combustible content of mixture ($Z_{c_{blend_{lower}}}$) [v/v%]		
NG 100%(v/v)	H_2NG 20%(v/v) H_2	H_2 100%(v/v)
4.20	4.16	4.00

When hydrogen is supplied, the lower flammability concentration limit of the combustible components of the gas mixture decreases slightly, dropping by 0.2 v/v%, as can be seen in *Table 7*. This reduction cannot be considered significant. However, knowing the result, the value of the lower flammability limit concentration can be further calculated using *Equation 10*

$$Z_{blend_{lower}} = Z_{c_{blend_{lower}}} \frac{1 + \frac{B}{1-B}}{1 + Z_{c_{blend_{higher}}} * \frac{B}{1-B}} \left[{m^3}/{m^3} \right] \tag{10}$$

where $Z_{c_{blend_{higher}}}$ is the lower ignition concentration limit of the mixture calculated on the combustible part [m^3/m^3], B is the inert content of the mixture [–].

When hydrogen is supplied in the natural gas infrastructure, the lower flammability concentration limit of the gas mixture decreases slightly by 0.24%(v/v), as can be seen in *Figure 2*. This may not be a high value, but knowing it is a key factor from a safety point of view.

3.8. Higher flammability limit of the gas mixture

The higher flammability limit (HFL) – also known as the upper flammability limit (UFL) – is the maximum concentration of a combustible gas in air above which the mixture cannot ignite or explode, even in the presence of an ignition source (Jiao et al., 2019). The first step to calculate the higher flammability limit of the natural gas-hydrogen mixture is calculating the higher flammability limit for the concentration of the combustible content of the gas mixture

$$Z_{c_{blend_{higher}}} = \frac{1}{\sum_{i=1}^{n} \frac{x_{ci}}{Z_{c_{higher\,i}}}} \left[{m^3}/{m^3} \right] \tag{11}$$

where x_{ci} is the volume ratio of combustible component to combustible material in the mixture [–], $Z_{c_{higher\,i}}$ is the higher flammability concentration limit for each combustible component [m^3/m^3].

Table 8

Higher flammability limit of the combustible content of the H_2NG mixture for hydrogen at 0, 20 and 100v/v%

Higher limit of flammability concentration of combustible content of mixture ($Z_{c_{blend_{higher}}}$) [%(v/v)]		
NG 100 %(v/v)	H_2NG 20 %(v/v) H2	H_2 100 %(v/v)
15.43	18.43	80.00

Under the influence of hydrogen feed, the upper flammability concentration limit of the combustible components of the gas mixture shows a clear increase of 64.57%(v/v), as shown in *Table 8*. Knowing the result, the value of the higher flammability limit concentration can be further calculated with *Equation 12*

$$Z_{blend_{higher}} = Z_{c_{blend_{higher}}} \frac{1+\frac{B}{1-B}}{1+Z_{c_{blend_{higher}}} * \frac{B}{1-B}} \left[{}^{m^3}/{}_{m^3}\right] \qquad (12)$$

where $Z_{c_{blend_{higher}}}$ is the upper flammability concentration limit of the mixture calculated on the combustible part [m^3/m^3], B is the inert content of the mixture [–].

Under the influence of hydrogen feed, the upper flammability concentration limit of the gas mixture shows a clear, significant increase of 64.40%(v/v). By including the non-combustible components in the equation, the bounds do not change significantly. However, when considering the values of methane and pure hydrogen, there is a very large difference, as can be seen in *Figure 2*. Broader flammability limits mean that a wider variety of gas concentrations becomes flammable, hence even small leaks may result in a flammable or explosive atmosphere.

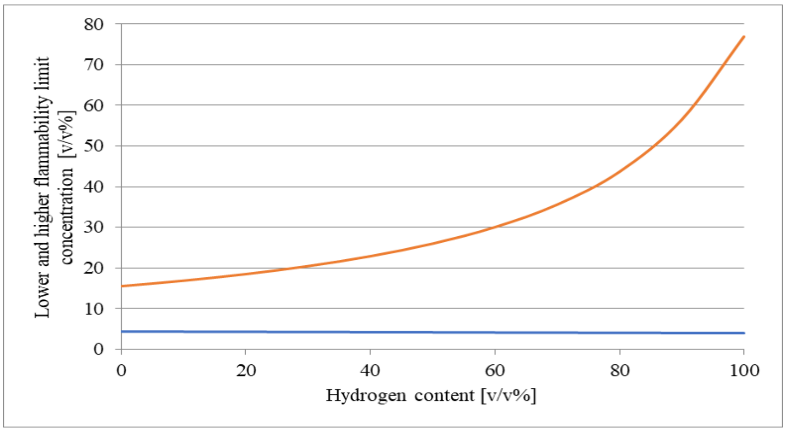

Figure 2

The effect of hydrogen blending on the lower and higher flammability limit concentration of the H_2NG mixture

4. CONCLUSIONS

Hydrogen produced from renewable energy sources can be incorporated into existing natural gas distribution systems or utilized directly at industrial sites. The resulting hydrogen-enriched fuel mixtures facilitate thermal and power generation with reduced greenhouse gas emissions, primarily due to hydrogen's superior combustion characteristics and lower carbon intensity compared to conventional natural gas. Therefore, hydrogen can be the energy carrier of the future, due to its promising combustion properties. As a result of our calculations, we found that the specific theoretical air requirement for perfect combustion is decreasing. The higher the hydrogen feeding, the fewer oxygen molecules are sufficient for perfect combustion. The flammability concentration limits for hydrogen-natural gas mixtures are wider than for natural gas only. The reason for this is that hydrogen has much wider ignition concentration limits than methane. Our calculations have led to the conclusion that the combustion characteristics of hydrogen–natural gas blends are significantly more complex than those of pure methane, introducing challenges in accurately modeling flame behavior and establishing reliable safety thresholds for operational use.

The biggest challenge related to this topic is whether natural gas using equipment can tolerate the presence of hydrogen or not, since these are the bottleneck of the network. An important consideration is the maximum hydrogen fraction that can be safely blended into natural gas without compromising the integrity of infrastructure, combustion performance, or safety standards. Furthermore, existing safety infrastructure – such as sensors, control valves, and ventilation systems – originally designed for pure natural gas applications may lack the sensitivity and response speed required to effectively detect and manage hydrogen-enriched mixtures, given hydrogen's higher reactivity and diffusivity.

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