This paper was presented at the Second International Symposium on Risk Analysis and Safety of Complex Structures and Components (IRAS 2023), 2-4 April 2023, Belgrade, Serbia

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LOW-CALORIE GASEOUS FUELS ENRICHMENT WITH HYDROGEN

OBOGAĆIVANJE NISKOKALORIČNIH GASOVITIH GORIVA VODONIKOM

Originalni naučni rad / Original scientific paper
UDK /UDC:
Rad primljen / Paper received: 25.05.2023

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Keywords
- hydrogen
- fuel cells
- biogas
- landfill gas
- safety asset
- improved combustion stability

Ključne reči
- vodonik
- gorivne ćelije
- biogas
- deponijski gas
- mere bezbednosti
- poboljšanje stabilnosti sagorevanja

Abstract

The quite certain introduction of hydrogen and mixtures of hydrogen and low calorific value gases (biogas and landfill gas) for the energy needs of modern society reveals a number of open questions related to the problems of applying these fuels in future commercial gas devices and systems. Currently, fuel cells are the only commercialized devices for using hydrogen. In the case of using hydrogen by the combustion method, there are already commercialized gas turbines of high power, while in the case of devices of lower power, manufacturers are still in the research and development phase. Serbia is given the opportunity to be in the process of developing the technology for the application of hydrogen in the energy sector.

Izvod

Sasvim je izvesno uvođenje vodonika i smeša vodonika i gasova niske kalorične vrednosti (kao što su biogas i deponijski gas) za energetske potrebe savremenog društva, što dovodi do niza otvorenih pitanja vezanih za probleme primene ovih goriva u budućim komercijalnim gasnim uređajima i sistemima. Trenutno su gorivne ćelije jedini komercijalizovani uređaji za korišćenje vodonika kao pogonske materije. U slučaju korišćenja vodonika u procesima sagorevanja, već postoje komercijalizovane gasne turbine velike snage, dok su kod uređaja manje snage proizvođači još u fazi istraživanja i razvoja. Srbija dobija priliku da bude u procesu razvoja tehnologije za primenu vodonika u energetskom sektoru.

HYDROGEN AS AN ADDITIVE FOR LOW CALORIFIC VALUE GASES

Hydrogen can be used as an additive for low calorific value gases in combustion to increase their energy content and improve their combustion properties. Low calorific value gases are gases that have low energy content and are usually produced from waste or biomass, such as landfill gas or biogas. These gases are often used for energy production in power plants, but their low energy content and variable composition can make combustion difficult and inefficient. Hydrogen, on the other hand, has high energy content and burns cleanly with no emissions of carbon dioxide or any pollutants. Adding hydrogen to low calorific value gases can increase their energy content, improve their combustion properties, and reduce emissions. Hydrogen can also help to stabilize combustion and reduce the risk of flameout, which can be a problem with low calorific value gases. However, there are also challenges associated with the use of hydrogen as an additive for low calorific value gases. One of the main challenges is that hydrogen is a highly flammable gas and requires special handling and safety precautions. In addition, the cost of producing and transporting hydrogen can be high, which can limit its use as an additive. Overall, the use of hydrogen as an additive for low calorific value gases in combustion can be an effective way to improve the energy content and combustion properties of these gases, but it requires careful consideration of safety, cost, and other factors. This principle is applicable to many low-calorie gaseous fuels (biogas, landfill gas, blast furnace gas). In the case of the production of renewable energy sources, the impact of adding hydrogen to biogas with a lower percentage of fuel components (CH_4), is particularly interesting. This type of hydrogen use could have a significant impact on the use of existing energy potentials related to both primary and secondary gaseous fuels in our country. One of the ways to achieve the above goals is to develop fuel flexible, low emission, low-cost burner, purposely designed and optimised, in order to be fuelled by renewable gases - biogas, landfill gases, and their blends with hydrogen. Biogases are usually utilised in specialized engines to generate power in the form of electricity and heat (CHP). The presence of hydrogen in fuel can be tolerated by up to 20 %, according to engine manufacturers, although there are some doubts about the proper type of engines and fuel feeding systems. Serbia is about to reach about 100 MW biogas-installed CHP plants which is the highest among the neighbouring countries. On the other hand, biogas is less often utilised in households, farming, and similar, mostly in less developed countries, using high emission, low efficient burners, and no hydrogen is expected to blend with biogas.

HYDROGEN

Hydrogen is the first and lightest chemical element. At standard conditions of pressure and temperature, hydrogen is a colourless, odourless, and tasteless diatomic gas. It is non-toxic and significantly lighter than air. The ease with which it ignites is the greatest danger in production, use and storage. It differs from other gases in that, when expanding from high pressures, it heats up, not cools down. Water is the most abundant natural resource in the world. Converting water into usable energy has always been man's dream. With the help of new technologies, hydrogen and oxygen gases can be generated from water. Currently, hydrogen is mostly produced from natural gas. The key way to obtain hydrogen is electrolysis, and in this way 'green' hydrogen is obtained. Hydrogen is a highly explosive gas and creates one of the highest flame temperatures. It is a very reactive element, with one valence electron. The character of the energy balance of hydrogen chemical reactions is exothermic in nature, which means that energy is released. Oxidation, that is, the burning of hydrogen molecules, creates a water molecule, making hydrogen the most environmentally friendly fuel. Due to its high reactivity, hydrogen can be added to other, low-calorie fuel gases, with a higher percentage of inert components in their composition, in order to improve the efficiency of the combustion process of such fuels. This fact can be very interesting and useful, considering the current situation on the natural gas market. Namely, we are aware of the current increase in the price and demand of natural gas in the world. Table 1 shows the heating values of the most frequently used gaseous fuels and hydrogen.

Table 1. The heating values for hydrogen and other common fuels.

	Hydrogen	Methane	Propane	Petrol
Higher heating value (25 °C, 0.101 MPa), kJ/g	141.86	55.53	50.36	47.5
Lower heating value (25 °C, 0.101 MPa), kJ/g	191.93	50.02	45.6	44.5

HYDROGEN PRODUCTION

Hydrogen can be produced from a variety of sources, including fossil fuels, biomass, and renewable energy sources. The most common methods of hydrogen production include:

- *Steam methane reforming*: this is the most common method of hydrogen production and involves the reaction of natural gas with steam to produce hydrogen and carbon dioxide. This method is widely used because natural gas is a readily available and relatively low-cost source of hydrogen.
- *Electrolysis*: this method involves passing an electric current through water to split it into hydrogen and oxygen. Electrolysis can be powered by renewable sources of electricity such as wind, or solar power, making it a promising source of clean, renewable hydrogen.
- *Biomass gasification*: this method involves heating biomass in the presence of oxygen to produce a gas mixture containing hydrogen, carbon monoxide, and other gases. The gas mixture is then cleaned and separated to produce hydrogen.
- *Thermochemical water splitting*: this method uses high temperatures and chemicals to break down water into hydrogen and oxygen. This method is still in the research and development phase but has the potential to be a more efficient and scalable method of hydrogen production.
- *Photo-biological water splitting*: this method uses photosynthetic organisms such as algae to produce hydrogen from water and sunlight. This method is still in the research and development phase but has the potential to be a sustainable and low-cost method of hydrogen production.

HYDROGEN BUOYANCY AS A SAFETY ASSET

Gaseous hydrogen has a density of 0.0838 kg/m^3 (at NTP) which is more than 14 times lower than that of air (1.205 kg/m^3) at the same conditions. The specific gravities of hydrogen and air at NTP are 0.07 and 1.0, respectively (Fig. 1), /1/. Therefore, hydrogen gas is lighter than air, and in ambient conditions it will rise and disperse in an open environment. As for other fuels, propane and petrol vapour are heavier than air, whilst methane, i.e., natural gas, is 2 times lighter than air, but almost 8 times heavier than hydrogen gas.

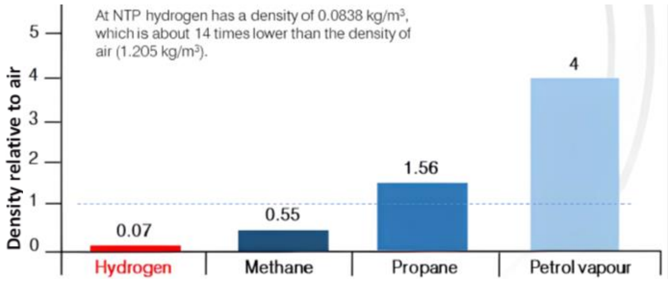

Figure 1. Densities relative to air for hydrogen and other common fuels.

MAIN OBSTACLES IN HYDROGEN PRODUCTION

There are several obstacles to large-scale hydrogen production, including:

- *Cost*: current hydrogen production methods can be relatively expensive compared to other fuels. For example, steam methane reforming requires large amounts of energy and produces carbon dioxide, which must be captured and stored to avoid environmental damage.
- *Energy efficiency*: some hydrogen production methods can be relatively inefficient, requiring large amounts of energy input to produce a given amount of hydrogen. This can limit the scalability and economic viability of hydrogen production.
- *Feedstock availability*: hydrogen production methods that rely on fossil fuels, such as steam methane reforming, are limited by the availability of these fuels. Biomass gasification and electrolysis are more sustainable options, but their scalability can be limited by the availability of feedstocks, such as biomass or renewable electricity.
- *Environmental impact*: some hydrogen production methods can have negative environmental impacts, such as the production of carbon dioxide or other greenhouse gases. This can limit the environmental benefits of hydrogen as a fuel source.
- *Storage and transport*: hydrogen is a highly flammable gas and requires careful handling during storage and transport. Current storage methods, such as high-pressure tanks or cryogenic storage, can be relatively expensive and limit the scalability of hydrogen as a fuel source.

TYPES OF HYDROGEN

There are several types of hydrogen, classified based on the way they are produced and the degree to which they are purified. The most common types of hydrogen include:

- *Gray hydrogen*: this is hydrogen produced from fossil fuels, such as natural gas, without any carbon capture or other emissions reduction technologies. Gray hydrogen is the most widely used type of hydrogen today and is often used in industrial processes.
- *Blue hydrogen*: this is hydrogen produced from fossil fuels, such as natural gas, with carbon capture and storage technologies to reduce greenhouse gas emissions. Blue hydrogen is a cleaner alternative to gray hydrogen and can be used in a wide range of applications, including transportation and power generation.
- *Green hydrogen*: this is hydrogen produced using renewable energy sources, such as wind or solar power, to electrolyse water into hydrogen and oxygen. Green hydrogen is a sustainable and zero-emissions form of hydrogen that has great potential to reduce greenhouse gas emissions and support the transition to a low-carbon economy.
- *Brown hydrogen*: this is hydrogen produced from coal using gasification or other technologies. Brown hydrogen is not widely used today and is considered a less sustainable alternative to gray or blue hydrogen.
- *Turquoise hydrogen*: this is hydrogen produced from natural gas using methane pyrolysis, a process that produces both hydrogen and solid carbon as byproducts. Turquoise hydrogen has the potential to be a low-carbon form of hydrogen if the solid carbon can be stored or utilised in a way that avoids greenhouse gas emissions.

HYDROGEN COMMERCIAL AND RESIDENTIAL APPLIANCES

If instead of being injected directly, some hydrogen is allowed to blend with methane and injected into the system, a major immediate safety concern would be the impact of that hydrogen on customer and commercial appliances. Given the challenge/inertia of requiring changes to end-use appliances, any changes would likely be introduced slowly as the blend percentage of hydrogen increases and as changes become necessary. Even so, adoption of new appliances would likely be phased in over a very long period of time given the low rate of appliance turnover (10-25 years), /2/. This is likely to be the greatest practical restriction on adopting high concentrations of hydrogen (at least 30 %) in the gas pipeline. Potential uses for hydrogen in the modern society are shown in Fig. 3.

MIXTURES OF HYDROGEN AND NATURAL GAS

Mixtures of hydrogen and natural gas can be used as a fuel source for combustion which can offer several benefits. Natural gas is a widely used and easily accessible fuel source, while hydrogen has a high energy content and produces no emissions of carbon dioxide or other pollutants. When combined, these two gases can create a cleaner and more efficient combustion process. However, there are also several challenges associated with using mixtures of hydrogen and natural gas for combustion. One of the main challenges is that hydrogen has different combustion properties than natural gas, which can affect the performance of the combustion process. In particular, hydrogen burns at a higher temperature and can result in higher NO_x emissions if not

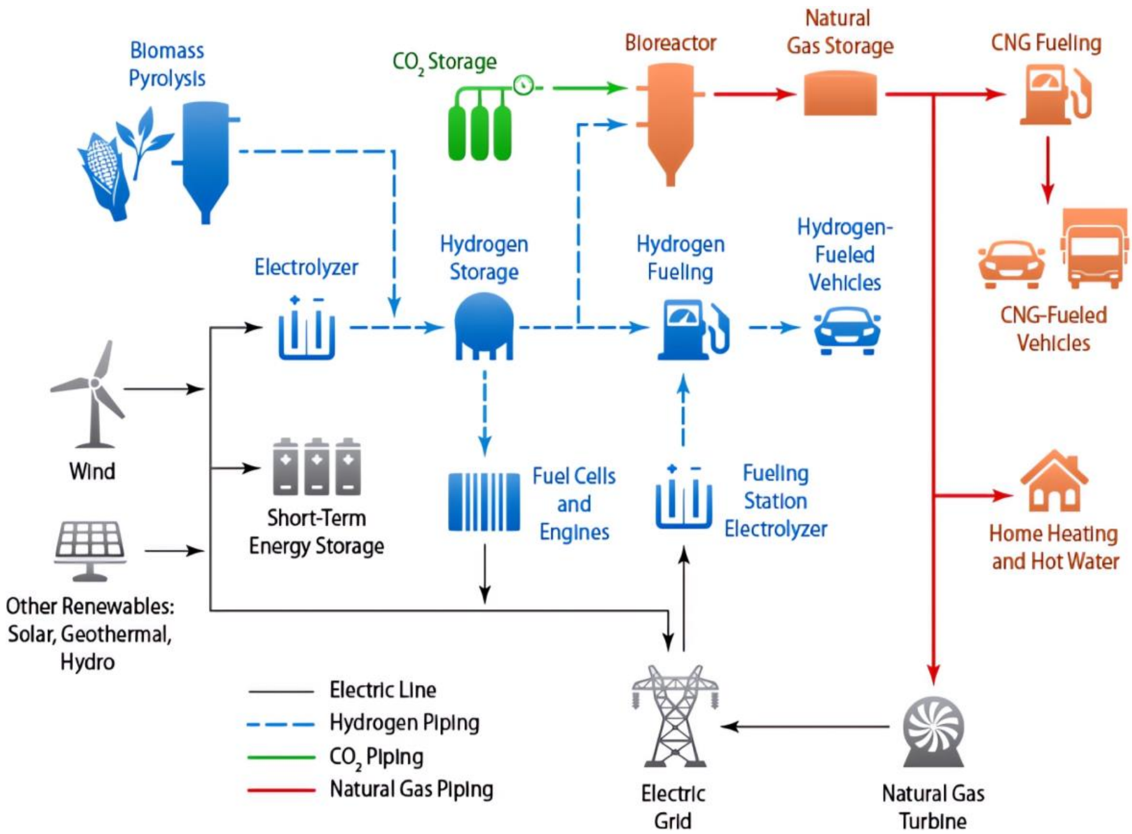

Figure 2. Hydrogen: a key part of future energy systems.

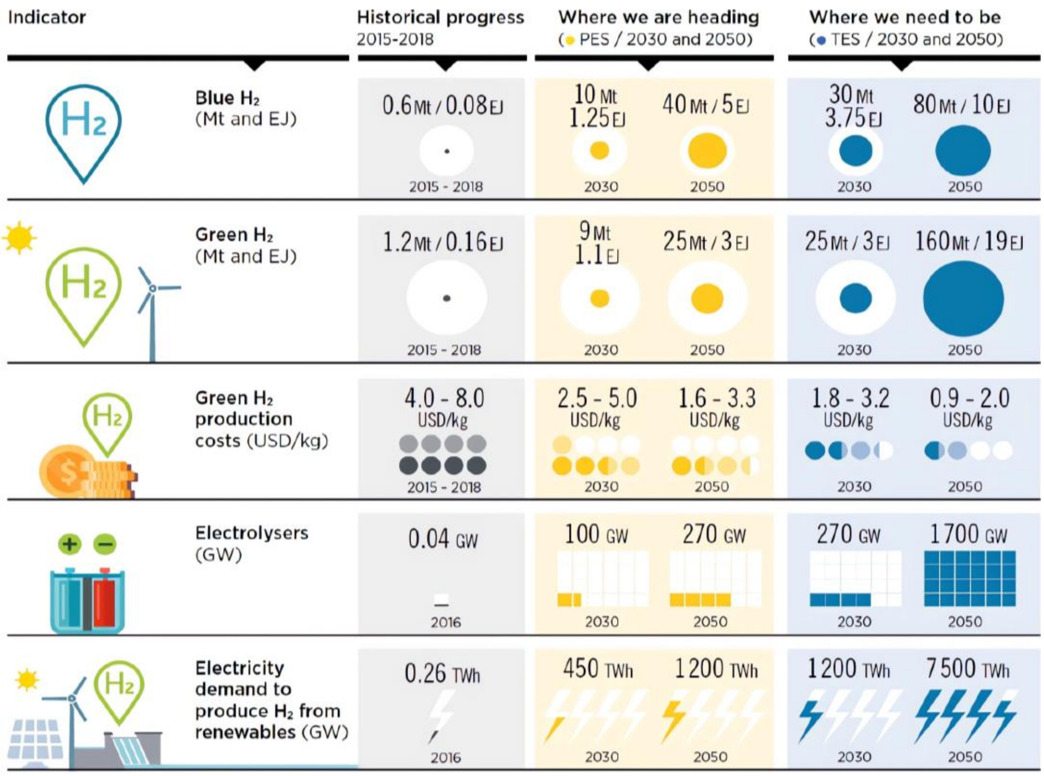

Figure 3. Potential uses for hydrogen in the modeoprn energy economy (U.S. Department of Energy, n.d.).

properly controlled. To address these challenges, several strategies can be employed. For example, the ratio of hydrogen to natural gas can be carefully controlled to optimise combustion performance and minimize emissions.

PHYSICAL EFFECT OF HYDROGEN ADDITION

Density and vapour pressure

Care must be taken in the choice of the amount of hydrogen in the H_2NG mixture since it significantly affects the density and vapour pressure of the gas. If the gas density is reduced the amount of hydrogen should be chosen according to the properties of the H_2NG mixture. Gases with lower density and higher vapour pressure could better fit for higher amounts of hydrogen in the H_2NG mixture.

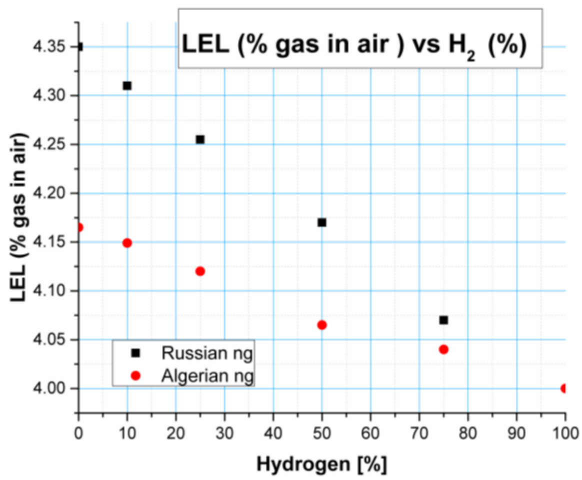

Figure 4. LEL of mixtures of two natural gases (Russian- and Algerian-type) at increasing concentrations of hydrogen (data calculated in reference to atmospheric conditions: 101.3 kPa and 20 °C.).

Lower explosion limits (LEL) of H_2NG

Gas mixing is in most countries a legal or regulatory requirement that specifies that natural gas in air has to be readily detectable at a concentration of 20-25 % of the LEL (Lower Explosion Limits). Hydrogen and natural gas have almost similar LEL values, so the LEL of the mixture does not change significantly when hydrogen is injected. Simulations were done to calculate the LEL of mixtures of two natural gases (Russian-type and Algerian-type) at increasing concentrations of hydrogen, as shown in Fig. 4.

HYDROGEN INJECTION INTO NATURAL GAS

France

In an experimental project (called GRHYD, coordinated by ENGIE from 2014 to 2020) hydrogen is injected progressively, up to 20 % in concentration, into natural gas in a local, new, and dedicated natural gas grid.

Germany

Several injections of hydrogen (with a concentration up to 2 %) into natural gas grids are operated. Near Hamburg, hydrogen is injected into the grid of Hanse Gas. In Frankfurt, hydrogen is injected into the local grid.

Italy

Up to now in Italy there are no injections of hydrogen into the natural gas grids. Anyway, there were experiences with mixing of manufactured gases. A confidential study dated 1983 refers on Rhino analytical controls of grids distributing natural gas and manufactured gas containing hydrogen. The composition of manufactured gas was roughly the following: methane 45 %; hydrogen 28 %; carbon monoxide 8 %; carbon dioxide 8 %; oxygen 2 %; nitrogen rest.

The Netherlands

During 2019-2020, research was organised by GTS and Netbeheer Nederland in order to state if increasing hydrogen concentrations can affect the effectiveness of gas mixture. DNV GL and SGS Nederland prepared 12 different mixtures of Groningen natural gas (L-gas) at four different concentrations of hydrogen (0 %, 15 %, 85 %, and 100 %).

United Kingdom

In October 2019, Hy4Heat published a report on 'Hydrogen Odorant' (Project Closure Report - Hydrogen Odorant and Leak Detection - Part 1- Hydrogen Odorant, from SGN), the aim of which was to identify a suitable odorant for use in a 100 % hydrogen gas grid (domestic use such as boilers and cookers). Research involved a selection of five odorants to be tested about the effects of the mixtures on pipeline (metal and plastic), appliances (a hydrogen boiler provided by Worcester Bosch) and PEM fuel cells.

MIXTURES OF HYDROGEN AND LANDFILL GAS

Mixtures of hydrogen and landfill gas can also be used as a fuel source for combustion which can offer similar benefits to the use of hydrogen and natural gas mixtures. Landfill gas is a low calorific value gas generated from the decomposition of organic waste in landfills. It typically contains around 50 % to 60 % methane, with the remainder being made up of other gases such as carbon dioxide, nitrogen, and trace amounts of other gases. However, as with mixtures of hydrogen and natural gas, there are also challenges associated with using mixtures of hydrogen and landfill gas for combustion. One of the main challenges is that landfill gas composition can vary widely depending on the age and composition of the waste being decomposed. This can make it difficult to control the combustion process and optimise performance. Additionally, hydrogen has different combustion properties than methane, the primary component of landfill gas. This can affect the performance of the combustion process and result in increased NO_x emissions if not properly controlled. To address these challenges, careful control of the hydrogen to landfill gas ratio is needed, as well as the design of combustion systems to account for the differences in combustion properties between hydrogen and methane.

MIXTURES OF HYDROGEN AND BIOGAS

Mixtures of hydrogen and biogas can also be used as a fuel source for combustion which can offer similar benefits to the use of hydrogen and other low calorific value gas mixtures. Biogas is a renewable fuel source that is produced through the anaerobic digestion of organic materials such as agricultural waste, food waste, and sewage sludge. Biogas typically contains around 50 % to 70 % methane, with the remainder being made up of other gases such as carbon dioxide, nitrogen, and trace amounts of other gases. The addition of hydrogen to biogas can increase its energy content and improve its combustion properties. This can result in a more efficient and cleaner combustion process, with reduced emissions of pollutants such as carbon monoxide and particulate matter. However, as with mixtures of hydrogen and other low calorific value gases, there are also challenges associated with using mixtures of hydrogen and biogas for combustion. One of the main challenges is that biogas composition can vary widely depending on the feedstock and the anaerobic digestion process used, /3/. This can make it difficult to control the combustion process and optimise performance.

MAIN OBSTACLES OF USING HYDROGEN AS AN ADDITIVE FOR LOW CALORIFIC VALUE GASES

There are several main obstacles to consider when using hydrogen as an additive for low calorific value gases in combustion. These include:

- *Safety concerns*: hydrogen is a highly flammable gas, and proper safety measures must be taken to ensure safe handling, storage, and transportation, /4/.
- *Cost*: hydrogen production is expensive, and the cost of producing and transporting hydrogen can be prohibitive, especially when compared to other fuel sources.
- *Infrastructure*: the existing infrastructure for the storage and transport of hydrogen is limited and may need to be expanded to support widespread use.
- *Combustion properties*: while hydrogen has many desirable combustion properties, it can also affect the combustion characteristics of other gases and may require adjustments to the combustion process.
- *Carbon emissions*: while hydrogen burns cleanly and produces no carbon dioxide emissions, the production of hydrogen can be associated with carbon emissions, depending on the source of the hydrogen.
- *Regulation*: there may be regulatory hurdles associated with the use of hydrogen as an additive for low calorific value gases, including safety standards, emissions regulations, and other requirements.

MAIN BENEFITS OF USING HYDROGEN AS AN ADDITIVE FOR LOW CALORIFIC VALUE GASES

Using hydrogen as an additive for low calorific value gases in combustion can offer several benefits:

- *Increased energy content*: hydrogen has a high energy content, so adding it to low calorific value gases can increase their overall energy content. This can improve the efficiency of the combustion process and reduce the amount of fuel needed to achieve the desired energy output.
- *Reduced emissions*: hydrogen combustion produces no carbon dioxide emissions and can significantly reduce other emissions such as particulate matter, carbon monoxide, and nitrogen oxides. This can make the combustion process cleaner and more environmentally friendly.
- *Improved combustion stability*: adding hydrogen to low calorific value gases can improve combustion stability by reducing the risk of flame extinction or instability. This can improve the overall performance and reliability of the combustion process, /5/.
- *Reduced fuel costs*: adding hydrogen to low calorific value gases can reduce the amount of fuel needed to achieve a given energy output, which can lower overall fuel costs. Additionally, hydrogen can be produced from renewable

sources, so using it as an additive can support the development of renewable energy technologies.

IMPROVED COMBUSTION STABILITY BY HYDROGEN IN COMBUSTIBLE GAS MIXTURES

Adding hydrogen to combustible gas mixtures can improve combustion stability in several ways:

- *Widening the flammability limits*: adding hydrogen to a combustible gas mixture can widen the range of fuel-to-air ratios over which the mixture can burn. This can increase the stability of the flame and reduce the risk of flameout or incomplete combustion, /6/.
- *Increasing flame speed*: hydrogen has a high flame speed compared to other combustible gases such as methane or propane. This can help to stabilize the flame and reduce the risk of flameout or flashback.
- *Reducing ignition delay*: hydrogen has a lower ignition delay time than other combustible gases, which means that it ignites faster and more easily. This can help to stabilize the flame and reduce the risk of incomplete combustion.
- *Enhancing heat transfer*: the addition of hydrogen to a combustible gas mixture can enhance heat transfer in the combustion process, leading to more complete combustion and higher combustion efficiency.

CONCLUSION

Main obstacles in hydrogen production must be addressed in order to scale up hydrogen production and support the development of a hydrogen economy. Research and development efforts are focused on improving the efficiency and reducing the cost of hydrogen production, as well as developing sustainable and environmentally friendly methods of production. Hydrogen production is a critical component of hydrogen economy and plays a vital role in the development of clean, sustainable energy technologies. The choice of hydrogen production method depends on factors such as cost, availability of feedstock, and environmental impact, /6/.

Choice of hydrogen type depends on factors such as cost, availability, and environmental impact. Green hydrogen is seen as the most promising type of hydrogen in terms of its sustainability and potential to reduce greenhouse gas emissions, but the development of low-emissions forms of blue and turquoise hydrogen can also play an important role in the transition to a low-carbon economy.

The use of mixtures of hydrogen and landfill gas for combustion can offer significant benefits in terms of energy efficiency and reduced emissions but requires careful consideration of the composition of landfill gas and the design of the combustion system.

Main obstacles for using hydrogen as an additive for low calorific value gases must be carefully considered when evaluating the feasibility and benefits of using hydrogen as an additive for low calorific value gases in combustion.

The use of hydrogen as an additive for low calorific value gases in combustion can offer significant benefits in terms of energy efficiency, reduced emissions, improved combustion stability, and lower fuel costs.

The improved combustion stability offered by adding hydrogen to combustible gas mixtures can lead to more reliable and efficient combustion processes with reduced emissions of pollutants such as carbon monoxide and nitrogen oxides. However, it is important to note that the use of hydrogen in combustion systems requires careful consideration of safety and operational issues such as flame speed, flashback, and hydrogen embrittlement, /7/.

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