

POTENTIAL OF HYDROGEN BLENDS

ALTERNATIVES FOR PROCESS DECARBONIZATION

*El potencial de las mezclas de hidrógeno.
Alternativas para el proceso de descarbonización*

Por:  Adriana Palacios Rosas · Pedro Manuel Castro Olivera · Zabdi Paulina Pérez Urquieta
· Eduardo Alejandro López López · Mariana Alejandra Vázquez López



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↪ **Recibido:** 9 de enero de 2024 ✓ **Aceptado:** 12 de marzo de 2024

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This study's objective is to analyze hydrogen mixtures as a solution for process decarbonization according to various compositions of mixtures and their effectiveness in reducing carbon emissions in industrial applications. The research focuses on quantitatively and qualitatively analyzing the efficiency of processes for a greener and low-carbon future in general terms. Within the results section, three experiments of specific mixtures where hydrogen is added are compared to analyze the height of the flame and, consequently, determine the relationship with

the percentage and concentration of the LPG and hydrogen mixture. In the first study, improvements were identified in LPG combustion by adding hydrogen to avoid a double flame structure. The second study highlights the addition of hydrogen to increase the fuel jet speed and the stabilization of the flame, so by adding hydrogen, energy savings in ranges over 70% are obtained. The third study shows that as the percentage of hydrogen changes, there are changes in the emission of pollutants and thermal characteristics of the flame. These articles derive potential applications in the emissions reduction in stoves

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according to the improvement of fuel blends and the use of hydrogen to optimize efficiency and heat transfer in power generation. In conclusion, the findings of the aforementioned studies support the importance of hydrogen in optimizing combustion processes, to improve efficiency and reduce emissions.

KEYWORDS

Hydrogen · Decarbonization · LPG- H_2 mixture · Energy efficiency · Sustainable processes

RESUMEN

El objetivo de este estudio es analizar mezclas de hidrógeno como solución para el proceso de descarbonización, según diversas composiciones de mezclas, y medir su eficacia en la reducción de emisiones de carbono en aplicaciones industriales. La investigación se centra en analizar cuantitativa y cualitativamente la eficiencia de los procesos para un futuro más verde y bajo en carbono en términos generales. Dentro del apartado de resultados se comparan tres experimentos de mezclas específicas a las que se añade hidrógeno, para analizar la altura de la llama y, en consecuencia, determinar la relación con el porcentaje y concentración de la mezcla de GLP e hidrógeno. En el primer estudio se identificaron mejoras en la combustión de GLP mediante la adición de hidrógeno para evitar una estructura de doble llama. El segundo estudio destaca la adición de hidrógeno para aumentar la velocidad del chorro de combustible y la estabilización de la llama, por lo que se obtienen ahorros energéticos en rangos superiores al 70 % mediante la adición de hidrógeno. El tercer estudio muestra que, a medida que cambia el porcentaje de hidrógeno, se producen cambios en la emisión de contaminantes y en las características térmicas de la llama. Dichos estudios se derivan como aplicaciones potenciales en la reducción de emisiones en estufas conforme a la mejora de mezclas de combustibles y la utilización del hidrógeno para la optimización de la eficiencia y la transferencia de calor en la generación de energía. En conclusión, con base en los resultados de los estudios mencionados se demuestra que el hidrógeno es importante en la optimización de procesos de combustión para mejoras en la eficiencia y la reducción de emisiones.

PALABRAS CLAVE

Hidrógeno · Descarbonización · Mezclas GLP- H_2 · Eficacia energética · Procesos sostenibles

INTRODUCTION

The urgent need for a global transition to cleaner and more efficient energy sources has become increasingly evident, driven by the need to decarbonize industrial processes and reduce greenhouse gas emissions. This urgency is aligned with the ambitious objectives set in the international agenda for 2030 and 2050, emphasizing the imperative need to combat climate change (Amin *et al.*, 2022; Brockway *et al.*, 2019; IEA, 2019). As the world experiences continuous modernization, energy consumption surges, placing an ever-growing demand on precious resources like fossil fuels (Hosseini & Wahid, 2016). This heightened demand serves as a stark reminder of the impending scarcity of fossil fuels, casting a long shadow on the future energy landscape (Hosseini *et al.*, 2013a).

The ramifications of such demand for a fossil-fuel-dependent lifestyle are formidable, presenting a looming threat in the form of accelerated global warming (Hosseini *et al.*, 2013b; Schnoor, 2004). Exploring cleaner and more efficient energy alternatives is crucial to alleviate the environmental impacts associated to traditional energy sources.

Rising greenhouse gas (GHG) emissions have propelled climate change to the forefront of global concerns, prompting policymakers and researchers to respond proactively (Amin *et al.*, 2022; Brockway *et al.*, 2019; IEA, 2019). The burning of fossil fuels for energy remains the largest contributor to climate change, particularly in industrialized nations (Full *et al.*, 2021). Energy-related emissions alone are responsible for approximately 81% of greenhouse gas emissions across Europe (Palma *et al.*, 2019), and a staggering 85% in Germany (Vizcaino *et al.*, 2012).

Amidst these challenges, the concept of e-fuels, or electrofuels, emerges as a promising avenue to reduce emissions and transition away from fossil fuels (Ueckerdt *et al.*, 2021). E-fuels are low-emission alternatives that have the potential to revolutionize the transportation sector, including light vehicles, heavy trucks, long-distance aviation, and industrial processes. The broad applicability of e-fuels signifies a cost-effective measure to drastically cut greenhouse gas emissions and meet the global 1.5 °C climate target, reducing the carbon footprint in both transportation and industry (Galimova *et al.*, 2023).

One notable candidate for clean and sustainable energy that has garnered significant attention in recent years is hydrogen. Hydrogen



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A PROFOUND
TRANSFORMATION OF
THE CURRENT ENERGY
INFRASTRUCTURE
(BARRETO ET AL., 2003).**

is the most abundant element in the universe, albeit it is not found in its free molecular form; it is typically bound in compounds (Grochala, 2015). Hydrogen can be derived from a variety of sources, including water, solid waste, wastewater, and biomass, making it an exceptionally versatile resource. Its production through thermochemical processes, such as coal gasification and natural gas reforming, boasts remarkable efficiency compared to electricity generation or the synthesis of alternative fuels like methanol (Lee *et al.*, 2023). A substantial portion of hydrogen production, approximately 79%, currently relies on natural gas reforming and coal gasification, with the remaining 21% produced as a by-product in refineries (Lee *et al.*, 2023).

The appeal of hydrogen as a clean fuel is underpinned by its remarkable characteristics. It is free of toxic emissions and possesses an energy efficiency of approximately 122 kJ/g, which is 2.75 times greater than that of hydrocarbon fuels (Karapinar & Kargi, 2006). Furthermore, hydrogen utilization does not give rise to the formation of toxic gasses or greenhouse gas emissions (Hosseini & Wahid, 2016). Its potential to be obtained from various processes, combined with effective logistics, positions hydrogen as a transformative alternative for economic growth (Palacios *et al.*, 2022). The production of hydrogen from fossil fuels, including natural gas and coal, results in the emission of greenhouse gases and is therefore not an environmentally clean process. For this reason, hydrogen generation with no negative impact is only obtained by using renewable energy (such as solar energy) (Nowotny & Veziroglu, 2011).

The journey towards a sustainable global energy system is an intricate, long-term endeavor that necessitates a profound transformation of the current energy infrastructure (Barreto *et al.*, 2003). While multiple sustainable energy pathways may emerge, the "hydrogen economy" has attracted significant

attention. A hydrogen-based energy system is deemed a viable and advantageous option for the delivery of high-quality energy services efficiently, cleanly, and safely; in line with sustainability objectives (Palacios *et al.*, 2022; Barreto *et al.*, 2003; Ogden, 1999).

Thanks to its straightforward electrochemical conversion, low weight, and impressive energy density, hydrogen can efficiently transport energy over considerable distances using liquid fuels, whether through cargo ships or pipelines. These attributes of hydrogen make it an ideal substitute for fossil fuels, contributing to its widespread recognition as a highly viable and eco-friendly alternative fuel (Aravindan & Kumar, 2023).

Hydrogen holds a unique position as an ideal complement to electricity. Both serve as premium energy carriers, devoid of carbon content and generating minimal or zero pollutant emissions at the point of use. However, hydrogen's advantage becomes apparent when energy storage is required, as it offers a practical solution for various applications.

A clear example is hydrogen's capacity to store large amounts of clean energy over extended periods for utilization during peak demand and seasonal energy balancing. Hydrogen can be produced through electrolysis, using surplus renewable electricity during peak production hours. After this, it can be employed in stationary fuel cells for power generation or stored as a compressed gas, cryogenic liquid, or a wide range of loosely bonded hydride compound for prolonged use. In times when renewable energy diminishes, for instance, when the sun sets in the case of solar energy, grid operators can activate hydrogen generators to maintain the supply of electricity until renewable energy is available again in the morning (FCHEA, n. d.).

The increased use of hydrogen in many countries underscores its potential to facilitate decarbonization and drive a sustainable energy transi-

Nomenclature

d	inner diameter of the nozzle (mm)
H	height of the flame from the nozzle-to-plate distance (mm)
Re	Reynolds number of the jet mixture, $Re = \frac{dV_{exit}\rho_{mix}}{\mu_{mix}}$
Re_{air}	Reynolds number of the air, $Re = \frac{dV_{air}\rho_{air}}{\mu_{air}}$
V_{air}	air velocity at 1 atm and 25 °C (m/s)
V_{exit}	fuel/air mixture flow velocity at the burner exit (m/s)

Greek

α	mole fraction of hydrogen in the fuel mixture
μ_{air}	air dynamic viscosity at 1 atm and 25 °C (kg/s-m)
μ_{mix}	dynamic viscosity of fuel/air mixture (N s/m ²)
ρ_{air}	air density at 1 atm and 25 °C (kg/m ³)
ρ_{mix}	density of fuel/air mixture (kg/m ³)
ϕ	fuel-air equivalence ratio of the mixture

tion. Hydrogen's versatility renders it a valuable transitional alternative in numerous applications, with the added benefit of being a non-greenhouse gas. However, hydrogen's complex nature, from production to utilization, poses challenges, particularly in terms of its relatively low volumetric energy density. This characteristic necessitates innovative solutions for storage and transportation (Lee *et al.*, 2023).

In the midst of these technological and environmental transformations, it is essential to recognize the broader context of energy access and its implications for developing countries. Approximately 18% of the world's population still lacks access to electricity, while 43% does not possess adequate cooking technologies. In rural areas, over half of the population lacks access to sufficient sanitation technologies, and approximately 22% lacks a reliable source of drinking water (Fuentes *et al.*, 2014). Small rural producers and subsistence farmers are particularly vulnerable to the unpredictable impacts of climate change, which is projected to affect developing nations most severely (Fuentes *et al.*, 2014).

To appreciate the significance of improved wood stoves in countries like Mexico, where firewood is the primary fuel for millions of people, one must consider that five million families live in conditions of poverty and marginalization, and still rely on open stoves for cooking, with a majority of them located in the central and southern regions of the country (Fuentes *et al.*, 2014). Furthermore, 90% of firewood users are concentrated in rural areas, highlighting the critical need for energy solutions in these underserved regions.

As we navigate the complex terrain of the energy transition, it is increasingly evident that the role of hydrogen and other clean energy sources is instrumental in reshaping our energy landscape. This article focuses on hydrogen mixtures and their applications, exploring their potential

as a versatile, sustainable, and efficient solution for decarbonizing industrial processes and addressing the pressing challenges of climate change and energy access. We delve into the intricate science behind hydrogen mixtures, their diverse applications, and the profound impact they can have on a global scale. In the quest for a sustainable future, hydrogen mixtures emerge as a beacon of hope, illuminating the path towards cleaner, more efficient, and accessible energy solutions.

The context of firewood in Mexico

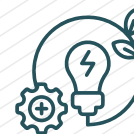
In Mexico, the problem of wood-burning stoves is presented as a double-sided challenge that affects both human health and the environment. Approximately 25% of households in the country rely on firewood as their main energy source, with this figure being even more pronounced in rural and indigenous communities in Southern Mexico (Palacios & Bradley, 2022). Wood-burning stoves operate through a transient batch process involving three stages: moisture evaporation, devolatilization, and charcoal combustion. This means that volatile materials are released when wood is burned, which in turn affects combustion conditions and heat production (Buggae *et al.*, 2019).

The widespread use of wood-burning stoves in Mexico presents two major problems. First, it is related to health problems, as these stoves emit noxious gases during combustion that negatively affect the respiratory system, increasing the risk of acute respiratory infections in children and chronic lung diseases in adults, in addition to releasing toxic, mutagenic, and carcinogenic compounds, such as oxygenated polycyclic aromatic hydrocarbons (Oxy-PAHs), and toxic metals in the ashes resulting from wood burning. Secondly, the widespread use of firewood as an energy source has contributed significantly to deforestation over almost

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HYDROGEN UTILIZATION DOES NOT GIVE RISE TO THE FORMATION OF TOXIC GASSES OR GREENHOUSE GAS EMISSIONS.

ITS POTENTIAL TO BE OBTAINED FROM VARIOUS PROCESSES, COMBINED WITH EFFECTIVE LOGISTICS, POSITIONS HYDROGEN AS A TRANSFORMATIVE ALTERNATIVE FOR ECONOMIC GROWTH.

Abbreviations

GHG	Greenhouse gas
LPG-air	Mixture of liquefied petroleum gas - air
LPG-fired	Mixture of liquefied petroleum gas - fired
LPG-hydrogen	Mixture of liquefied petroleum gas - hydrogen
LPG-H ₂ -IDF	Inverse diffusion flame in the blend liquefied petroleum gas and hydrogen
LPG-IDF	Inverse diffusion flame with liquefied petroleum gas
OH-PLIF	Oxygenated polycyclic aromatic hydrocarbons
PAHS	Planar laser-induced fluorescence of hydroxyl
RFG	Refinery fuel gas



THE DIVERSIFICATION OF ENERGY SOURCES, INCLUDING THE USE OF LESS ENVIRONMENTALLY DAMAGING FUELS, CAN PLAY A CRUCIAL ROLE ON THE ROAD TO A MORE SUSTAINABLE MEXICO.

70% of Mexico, especially in the southern and central states of the country, which has a negative impact on the environment and the sustainability of forest resources in the long term.

In this context, the need to explore alternatives that address both health concerns and environmental sustainability becomes evident. The transition to cleaner and more efficient fuels and technologies is presented as a viable solution to mitigate the negative effects of wood stoves in Mexico. The adoption of cleaner cooking technologies, such as gas or electric stoves, can contribute to the reduction of adverse health impacts, while reducing pressure on forest resources and consequent deforestation. The diversification of energy sources, including the use of less environmentally damaging fuels, can play a crucial role on the road to a more sustainable Mexico.

Experimental results

In the following section, three experimental research studies have been considered and analyzed (Cheung *et al.*, 2012; Miao *et al.*, 2014; Cheung *et al.*, 2016). These are related to (i) the addition of H₂ on OH distribution of LPG-air circumferential inverse diffusion jet flames; (ii) the effect of hydrogen percentage and air jet Reynolds number on fuel flame lean stability of LPG-fired inverse diffusion jet flames with hydrogen enrichment; and (iii) the effect of hydrogen concentration on the emission and heat transfer of premixed LPG-hydrogen jet flames. The first study shows how LPG combustion can be improved by adding hydrogen to avoid a double flame structure. In the second study, hydrogen is added, increasing the fuel jet speed and flame stability, thereby saving energy in ranges greater than 70%. The third study shows that there are changes in the thermal characteristics of the flame and emission of pollutants as the percentage of hydrogen changes. Therefore, the findings of these three studies highlight the importance of hydrogen for the optimization of combustion processes, especially in terms of improving efficiency and reducing emissions.

Experiment 1: The effect of the addition of hydrogen on OH distribution of LPG-air circumferential inverse diffusion flames

As a first investigation, the article "The effect of the addition of hydrogen on OH distribution of LPG/Air circumferential inverse diffusion flames" (Cheung *et al.*, 2016) was considered.

Firstly, this research considers the percentage of hydrogen and nitrogen, Reynolds number of the central air jet, and total air-fuel equivalence ratio. Also, in the fuel combination, the radius of propane and butane are fixed, while the percentage of hydrogen varies from 0% to 100%, increasing by 10% in each experiment.

Figure 1 shows the behavior of the jet flames with the addition of hydrogen to LPG-IDF mixtures. It can be determined that at low percentages of hydrogen (0% - 40%) the reaction zones determined by OH-PLIF are thin and short. Also, strong OH concentrations are detected at the periphery of the base of the flame where it reflects the combustion of fuel jets with ambient air and, on the other hand, weak OH concentrations are detected along the periphery of the flare in the flame, resulting in the remaining fuel burning with the ambient air and central jet air. In addition, the high-velocity central air jet penetrates through the flame where it is created as an open tip.

It is evident that as the hydrogen percentage increases, the combustion zone expands downstream, exhibiting flow acceleration and a longer jet flame because the variables are fixed (figure 1). When the hydrogen percentage is low, the required ignition energy of the fuel mixture is high and some of the fuel is cooled and extinguished by mixing with the central air jet. Therefore, the concentration of OH decreases severely after passing the flame neck, where the fuel jets only impinge on the central air jet.

Experiment 2: The effect of hydrogen percentage and air jet Reynolds number on fuel lean flame stability of LPG-fired inverse diffusion jet flames with hydrogen enrichment

A second article, "The effect of hydrogen percentage and air jet Reynolds number on fuel lean flame stability of LPG-fired inverse diffusion flame with hydrogen enrichment" (Miao *et al.*, 2014), was considered. In this article, 15 different experiments were carried out by varying the Reynolds number of the central air jet (Re_{air}) to investigate the fuel flow needed to reach a stable flame.

Table 1 shows that the addition of hydrogen increases the minimum fuel flow required to maintain a full flame when the flow rate decreases and the flame restoration limit increases, especially by a percentage of hydrogen greater than 70. This means that the flame

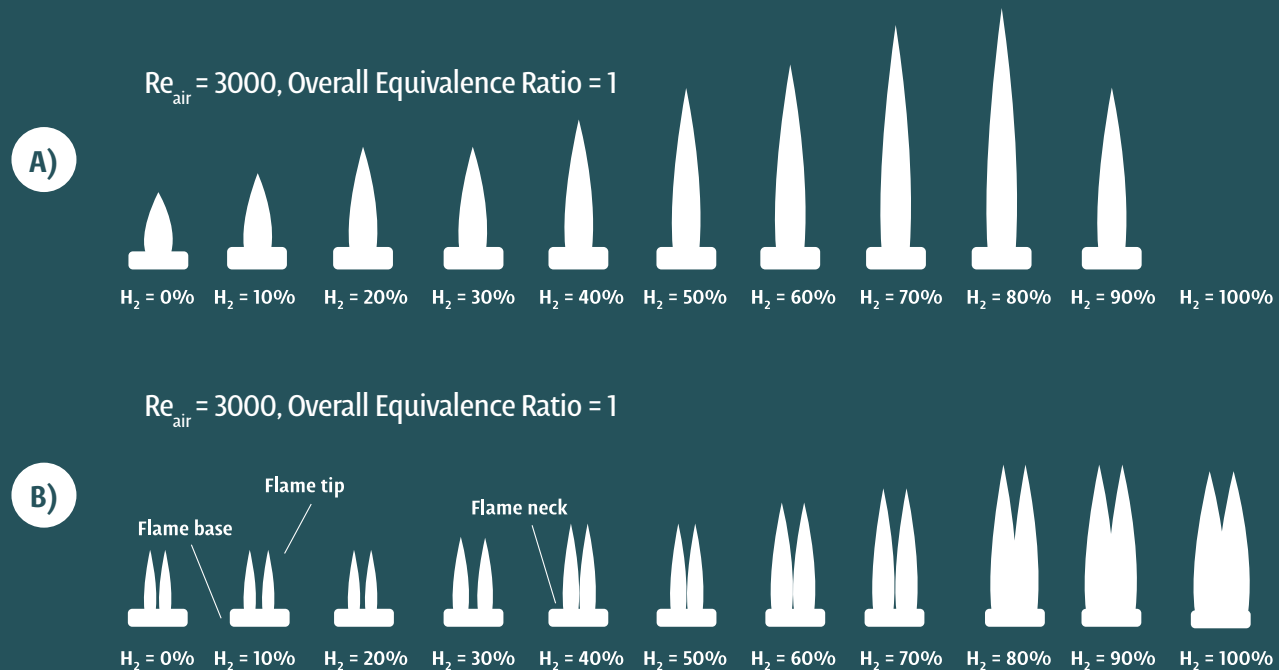


Figure 1. The effect of adding hydrogen on the flame structure of LPG-IDF: (a) flame image; (b) OH-PLIF result. Adapted from Cheung *et al.* (2016).

will require more fuel to restore its full shape, since hydrogen reduces the volumetric calorific value of the fuel mixture and there is not enough heat to withstand a flame front. Table 1 also shows the properties regarding the LPG/H₂ fuel mixture, where its hydrogen percentage varies with a difference in density, lower heating value (LHV), and the stoichiometric relationship of air and fuel.

The data from figure 2 indicates that a pure LPG IDF (inverse diffusion jet flame) can be recovered to a full flame with a lower fuel flow rate than LPG-H₂ IDF, where an insufficient flow rate can be excluded from the reasons for local extinction in LPG-H₂ IDF to fill all fuel ports. The fall of the complete extinction limit is not so significant when the hydrogen percentage is above 30%. It should be clarified that the flame implies a higher restoration limit in its full form by adding more than 70% hydrogen because the addition of hydrogen reduces the volumetric calorific value of the mixture.

From the data and experimental phenomena, shown in figure 2, it can also be seen that an LPG IDF is capable of maintaining the incomplete flame form for a narrow fuel flow velocity range, and complete extinction usually occurs almost immediately when the fuel flow rate reaches the critical level, where this is important to check in regards to the addition of hydrogen in the mixture.

The effect of hydrogen enrichment is also seen to be most noticeable for a hydrogen percentage below 50%, and a greater addition of hydrogen results in a slight increase in the equivalence ratio required at the restoration limit. Furthermore, adding hydrogen to LPG is shown to reduce the stoichiometric air/fuel volumetric ratio of the fuel mixture, and this phenomenon means that more fuel is needed to achieve the same equivalence ratio.

When the percentage of hydrogen is greater than 30% (figure 3), the flame has been found to be completely extinguished with similar overall energy consumption rates, while the local extinction limit has been found to drop dramatically as the addition of hydrogen increases. The reason that the flame is stable with a lower energy supply rate following the addition of hydrogen may be due to an improvement in the air/fuel mixture caused by the high combustion rate and diffusivity of hydrogen.

The data shown in figure 3 can be interpreted as proof of improved stability when applying the LPG-H₂ IDF.

Experiment 3: The effect of hydrogen concentration on the emission and heat transfer of a premixed LPG-hydrogen flame

A third article, "The effect of hydrogen concentration on the emission and heat transfer of a premixed LPG-hydrogen flame" (Cheung *et al.*,

Table 1. Properties of fuel mixture with various hydrogen percentages (Miao *et al.*, 2014).

H ₂ % (vol.)	Fuel mixture density (g/L)	Stoichiometric air /fuel ratio (vol.)	Weight LHV (MJ/kg)	Volumetric LHV (MJ/m ³)
0	2.20	28.8	45.91	101.23
10	1.99	26.2	53.32	106.25
20	1.78	23.5	60.73	108.12
30	1.57	20.9	68.14	106.85
40	1.36	18.2	75.55	102.43
50	1.14	15.6	82.96	94.87
60	0.93	13.0	90.37	84.17
70	0.72	10.3	97.77	70.31
80	0.51	7.7	105.18	53.32
90	0.29	5.0	112.59	33.18
100	0.08	2.4	120.00	9.89

Global Energy Consumption Rate at Stability Limits, Hydrogen Percentage = 50%

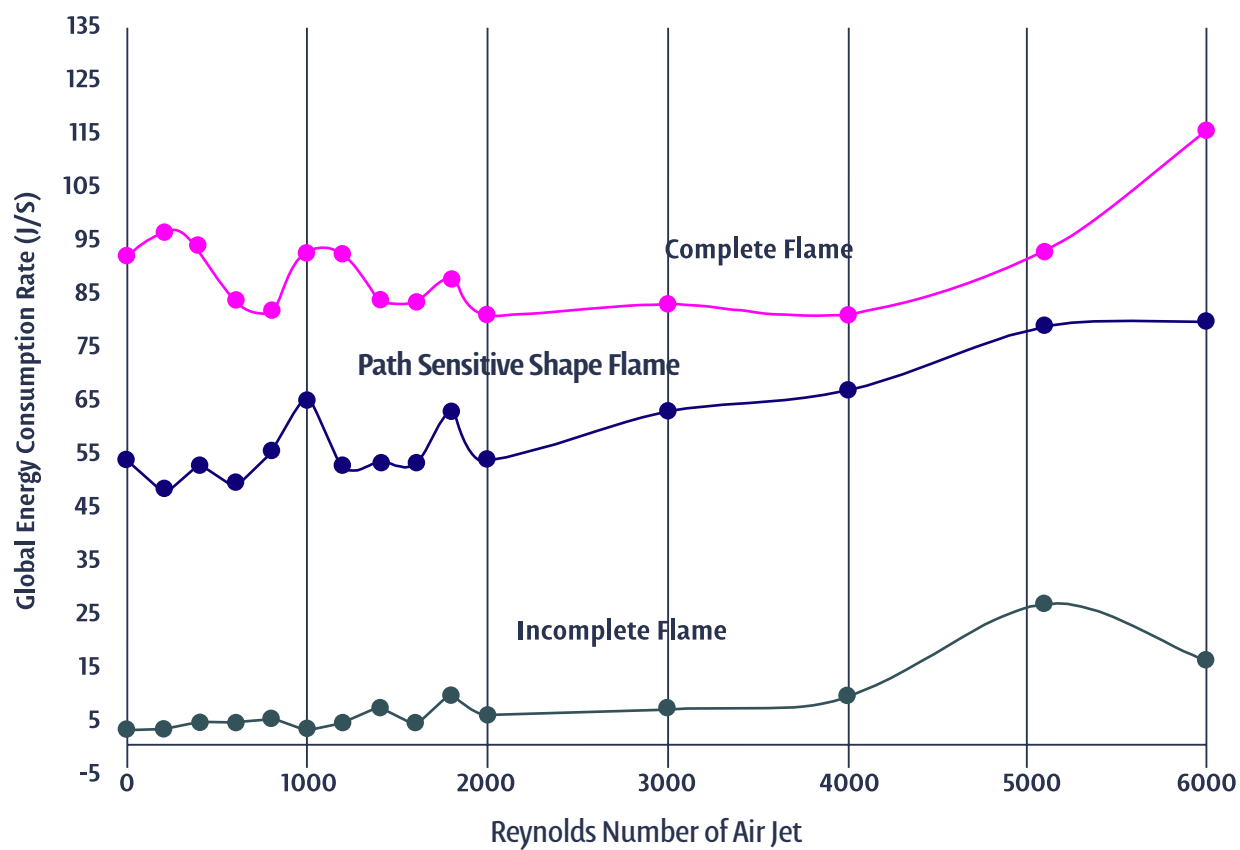


Figure 2. The effect of hydrogen percentage on fuel jet velocity at three limits of LPG-H₂ IDF under hydrogen percentage = 50%. Adapted from Miao *et al.* (2014).

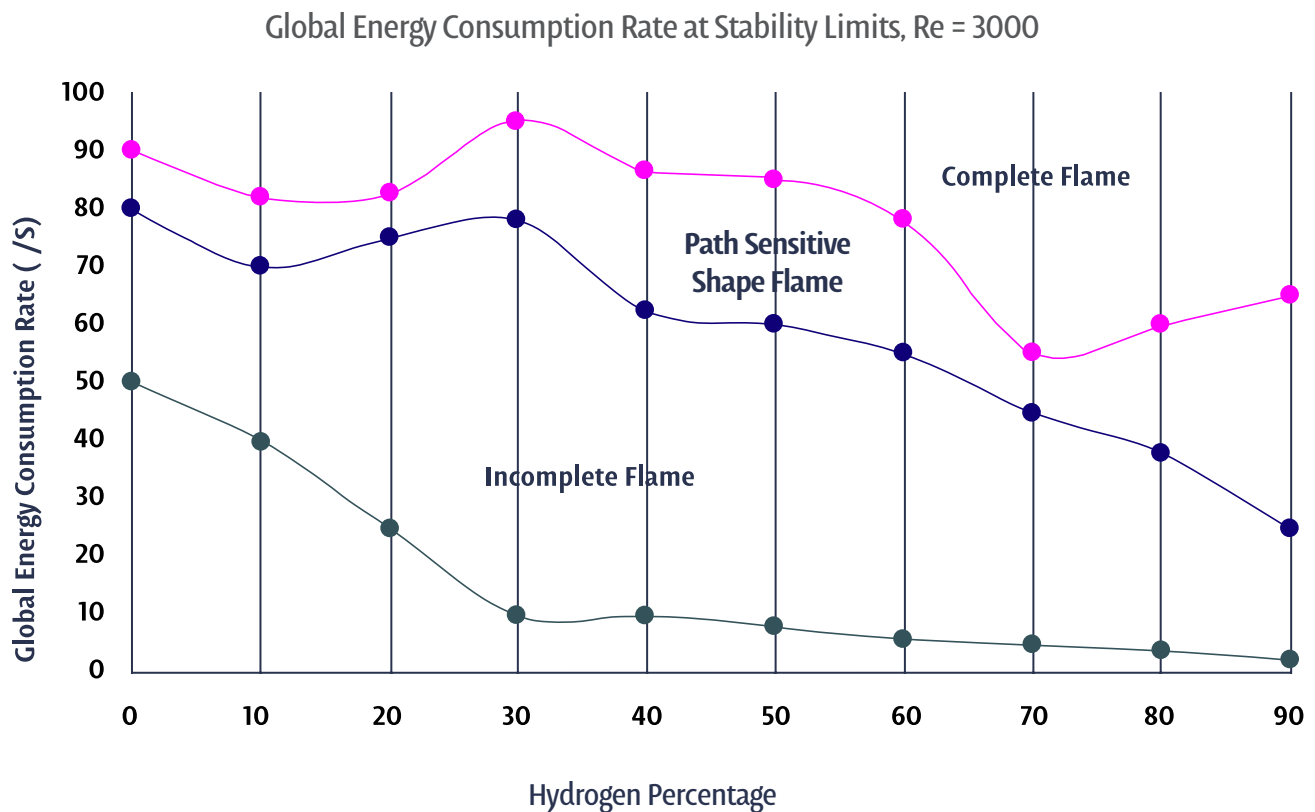


Figure 3. The effect of hydrogen percentage on global energy consumption rate at three stability limits of LPG- H_2 IDF under $Re_{air} = 3000$. Adapted from Miao *et al.* (2014).

2012), was considered. It concerns an experimental study on the effect of hydrogen concentration on the emission and heat transfer characteristics of a laminar premixed LPG-hydrogen jet flame. In Cheung *et al.*'s (2012) experiments the mole fraction of hydrogen in the fuel mixture varied from 0% to 50%. The equivalence ratio of the fuel/air mixture was kept at stoichiometry and the mixture jet Reynolds number was fixed at $Re = 1500$ for most of the tests. Several layers of meshed screens were installed at the base of the tube to produce a uniform velocity distribution at the exit plane of the tube and prevent flashback. The LPG and hydrogen were supplied from high-pressure cylinders. The fuels used were commercial-grade LPG, consisting of 70% butane and 30% propane by volume, and H_2 with 98% purity.

The results have shown that, upon varying the hydrogen content in the fuel mixture, there is a corresponding change in the appearance, pollutant emissions, and heat transfer characteristics of the flame (Cheung *et al.*, 2012).

It has also been observed that each flame appeared as a stationary flame attached to the burner nozzle, where a blue conical flame front was formed, as shown in figure 4.

Figure 4 shows that no variation is observed in flame shape and color with or without the addition of hydrogen. Furthermore, in all the flames, the flame front is conical in shape and blue in color, indicative of the dominance of LPG combustion over the features of hydrogen combustion. This is because, even at the highest level of hydrogen concentration (50%), the mass proportion of hydrogen in the fuel is as low as 3.6%, and accordingly the energy content of hydrogen in the fuel is below 9%, indicating that most of the heat released is from the burning of LPG, rather than hydrogen (Cheung *et al.*, 2012).

Figure 5 presents these results for the baseline flame and the flame with a 50% hydrogen addition. It is shown that the peak flame temperature occurs at the tip of the flame front. In the regions near the flame tip, including both the upstream preheat region and the post-flame region, the flame with hydrogen addition has a significantly higher temperature than the pure LPG flame (Cheung *et al.*, 2012).

Figure 5 demonstrates that, with the addition of hydrogen in the LPG fuel, the flame temperature starts to increase. The increase in the peak flame temperature shows a linear trend. For both data sets, the increase is within 30 K, indicating



THE RESULTS HAVE SHOWN THAT, UPON VARYING THE HYDROGEN CONTENT IN THE FUEL MIXTURE, THERE IS A CORRESPONDING CHANGE IN THE APPEARANCE, POLLUTANT EMISSIONS, AND HEAT TRANSFER CHARACTERISTICS OF THE FLAME (CHEUNG ET AL., 2012).

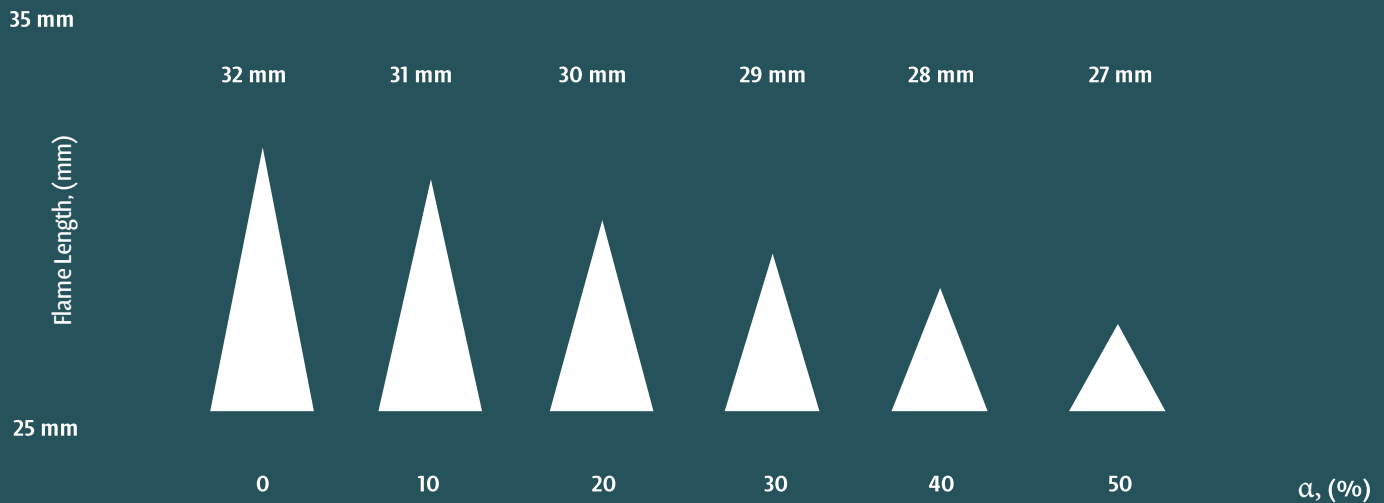


Figure 4. Heights of the flames against hydrogen content at $Re = 1500$ and $\Phi = 1$. Adapted from Choy *et al.* (2012).

less than 2% increase, as it varies from 0% to 50% hydrogen addition. This slight linear modification of the flame temperature with respect to hydrogen addition is due to the linear increase of the energy input (Cheung *et al.*, 2012).

On the other hand, it is proposed that the radiative heat loss from the flame decreases monotonically from the baseline condition to the 50-50% mixture of LPG- H_2 , because CO_2 and soot production rates drop as more hydrogen and less LPG is supplied to the flame (Cheung *et al.*, 2012).

◆ RESULTS AND DISCUSSION

The three investigations presented (Cheung *et al.*, 2012; Miao *et al.*, 2014; Cheung *et al.*, 2016) provide valuable information on the use of hydrogen in different aspects of gas mixture combustion. These studies mention relevant insights to address emission reduction in stove, boiler, and engine-related applications, and consider factors such as efficiency and heat transfer, data mixing, the effect of height and length, and flame behavior.

The first investigation, by Cheung *et al.* (2016), explored the effect of adding hydrogen to the OH distribution in LPG-air circumferential diffuse inversion flames. The results indicated that the addition of hydrogen to LPG-IDF mixtures had a significant impact on the flame structure.

The second investigation, by Miao *et al.* (2014), focused on the effect of the percentage of hydrogen and Reynolds number of the air jet on the lean flame stability of hydrogen-enriched LPG flames. The results showed

that the addition of hydrogen increased the minimum fuel flow required to maintain a full flame and this has important implications for combustion efficiency and flame stability in stove and boiler applications. In addition, it was observed that the effect of hydrogen enrichment was most noticeable when the percentage of hydrogen was below 50%.

The third investigation, by Cheung *et al.* (2012), focused on the effect of hydrogen concentration on the emissions and heat transfer of LPG-hydrogen premixed flames. The hydrogen concentration had an impact on flame temperature and radiant heat loss. As the hydrogen concentration increased, the flame temperature increased. This could be relevant for improving efficiency in applications where high heat transfer is required. In addition, it was observed that the radiant heat loss decreased as more hydrogen was added to the fuel mixture.

In summary, the research presented above provides a deeper understanding of how the addition of hydrogen to fuel mixtures affects flames, combustion efficiency, and emissions. These findings have potential applications in reducing emissions in stoves and boilers by optimizing the fuel mixture and better understanding how hydrogen influences combustion. In addition, important considerations related to efficiency and heat transfer are highlighted, which may be crucial to improve the performance of heating and power generation systems. Data mixing and flame behavior are fundamental aspects to consider when implementing this research in practical applications.

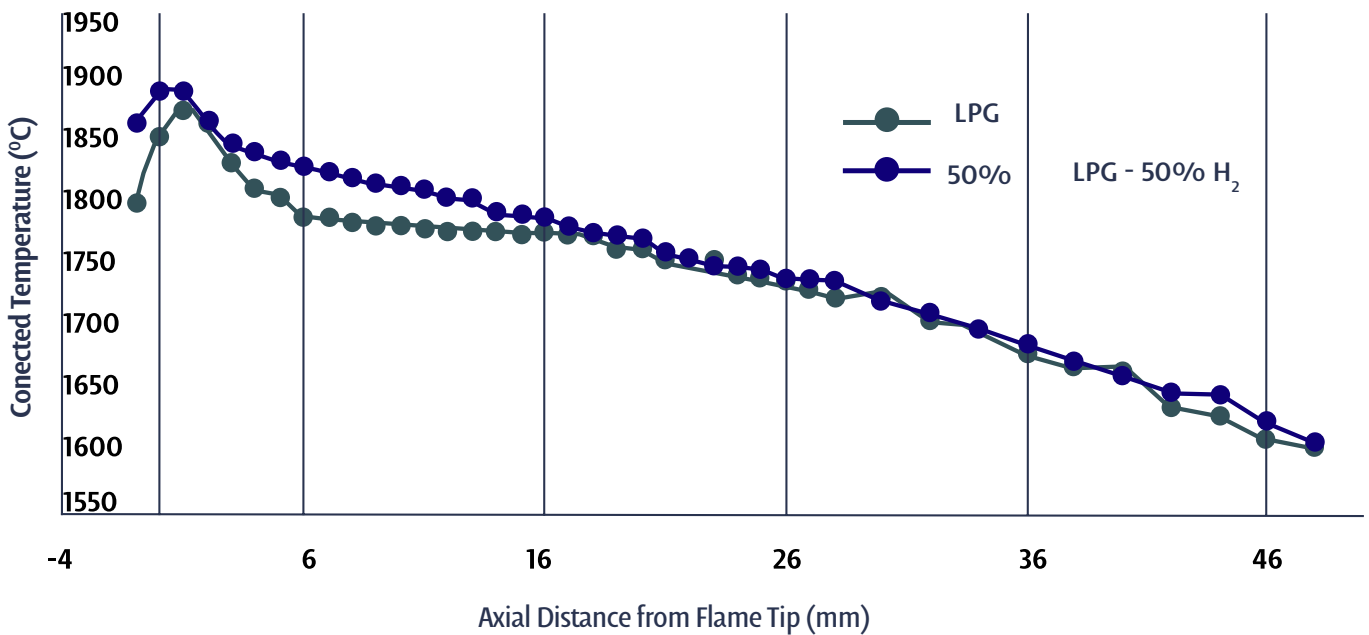


Figure 5. Temperature along the axis of the flames at $Re = 1500$ and $\Phi = 1$. Taken from Cheung *et al.* (2012).

Applications

Stoves

In the United Kingdom, the HyDeploy project is the first to demonstrate that hydrogen can be safely mixed into the natural gas distribution system without changes to appliances and associated disruption.

HyDeploy consists of three stages: the first is a technical program to allow the injection of 20% mol hydrogen, the second is in reference to the construction of the electrolyser unit and input to the network for the mixture of hydrogen and injection into the Keele University gas distribution project network, and the third is a ten-month process to support the path to fully blended gas deployment (Isaac, 2019).

The purpose of this project is to develop sufficient evidence that hydrogen can be blended into an operating UK natural gas network without disrupting customers and without compromising the safety of end users. In addition, it is a fundamental project for the decarbonization of the gas network through the deployment of hydrogen and will provide the first step to establish the technical, operational, and regulatory background of the hydrogen vector (Isaac, 2019).

Boilers

Another possible application for hydrogen has been demonstrated through the use of a boiler, as pointed out by Büyükakın and Öztuna (2020). In their study, a mixture of hydrogen and methane was used, which was simulated using a CFD

APPLICATIONS

THE RESEARCH PRESENTED PROVIDES A DEEPER UNDERSTANDING OF HOW THE ADDITION OF HYDROGEN TO FUEL MIXTURES AFFECTS FLAMES, COMBUSTION EFFICIENCY, AND EMISSIONS. THESE FINDINGS HAVE POTENTIAL APPLICATIONS IN REDUCING EMISSIONS BY OPTIMIZING THE FUEL MIXTURE.

STOVES

BOILERS

ENGINES



THE IMPLEMENTATION OF HYDROGEN CONSTITUTES A VIABLE ALTERNATIVE TO ELIMINATE OR REDUCE CARBON DIOXIDE EMISSIONS, THUS HELPING TO REDUCE THEIR ENVIRONMENTAL IMPACT.



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and Fluent code. Likewise, the study was simulated with a boiler that used natural gas. For this type of boiler, a constant fuel input of 45 Nm³/h was established, while the coefficient for the excess air ratio fluctuated between 1.2 and 1.35. The considerations for the mixture of hydrogen and methane were established by defining mixtures that contained various percentages of hydrogen fuel by mass, such as 0%, 25%, 50%, and 75%, while for the combustion chamber a heat capacity of 432 kW was defined (Büyükkakin & Öztuna, 2020).

Büyükkakin and Öztuna (2020) subsequently point out that with the results obtained a numerical analysis was carried out, in which they calculated and validated the experimental measurements of temperature and emission of combustion gasses for each of the two cases. Thus, it was possible to verify that the enrichment of methane with hydrogen reduces carbon emissions, while it substantially increases the formation of thermal NO emissions.

Engines

The mixture of hydrogen and diesel increases the combustion process and the power of the engine at all its loads. The air-fuel ratio and a minimum percentage of hydrogen addition affect the speed of maximum power output. Likewise, if hydrogen exceeds a range greater than 30%, the engine's power will be affected (Gheorghe *et al.*, 2019).

An application of 5% of hydrogen in a fuel mixture reduces the duration of ignition, however, it improves the performance of the engine. It should be clarified that the hydrogen should not exceed 15%, as this would cause a severe blow to the engine (Gheorghe *et al.*, 2019).

The high speed of the hydrogen flame enables the approximation to an engine with an ideal thermodynamic cycle, grants combustion in engines in fuel-air mixtures, and demands engine parts with a higher value compared to the implementation of petrodiesel fuels (Gheorghe *et al.*, 2019).

The advantages of hydrogen implementation: future challenges and opportunities

The implementation of hydrogen constitutes a viable alternative to eliminate or reduce carbon dioxide emissions, thus helping to reduce their environmental impact. The commitment to use hydrogen as the "fuel of the future" will allow modern society to maintain the energy generation and transportation capacities it requires.

Hydrogen emerges as a promising and viable renewable energy carrier, with the potential

to significantly accelerate the process of scaling up clean and renewable energy. It is crucial for governments to enact measures to promote the conservation of oil supplies, such as gasoline and petroleum. The development of technology, energy system optimization, and increased energy efficiency could reduce the cost of energy. The primary actions to be considered should be strengthening the regulatory framework, improving and implementing state support measures for hydrogen energy projects, supporting the positions of companies in the hydrogen sales market, and engaging in research and development. Funds should be mobilized towards investment in the deployment of green energy; although public sector funds will persist in promoting investments in green energy, a larger portion of future financial commitments to green energy initiatives should originate from the private sector. Furthermore, it is important to prioritize efforts aimed at diminishing the global expenses associated with deploying green energy, accelerating the provision of funding and technical assistance, establishing economies of scale, and fostering both domestic and international trade (Deep *et al.*, 2023). Another big challenge for the development of hydrogen technology, in addition to ensuring its efficient large-scale production, is the ability to store it in a compact and safe place (López, 2018).

The energy density of hydrogen is higher than that of conventional fossil fuels. In addition, it can be used as a raw material in fuel cells, which can produce electricity with an efficiency of up to 60%, because they are not subject to the Carnot cycle. In other words, it is a more efficient process than internal combustion engines. It has a high heat of combustion (572 kJ/mol) and is compatible with the environment since its only combustion product is water (Berry & Salvador, 2006), which contributes to the slowdown of climate change (López, 2018; Muñoz, 2015). Therefore, although hydrogen presents a diversity of challenges in terms of production, storage, raw materials, and mature technologies, as well as others such as legislation and social acceptance, it has great potential as a fuel, which has caused it to become a global trend that continues to grow in terms of research and development.

For some time now, Mexico has found itself in a dualism of political ideals with respect to the issue of clean energy due to the fact that the government privileges the exploitation and use of fossil fuels to a greater extent, and therefore does not promote the necessary conditions to carry out an inclusive, participatory, and dem-



MEXICO HAS THE POTENTIAL TO IMPLEMENT A NEW ENERGY STRATEGY, WHICH WOULD ALLOW THE COUNTRY TO GROW AS AN APPLICATION POWERHOUSE FOR NEW AND EXISTING PROCESS AREAS.

ocratic energy reform that would allow the participation of society in the decision-making process regarding the country's economic, social, and environmental problems (Ley para el Aprovechamiento de Energías Renovables y el Financiamiento de la Transición Energética, 2012). Fortunately, the Mexican government is currently undergoing an energy transition with the aim of leading the country towards sustainable development through the dissemination of clean energy projects, participation in energy decisions, implementation of methodologies appropriate to social and environmental sectors, choice of sustainability criteria, and studies on the exploitation of non-renewable fuels (Ley General del Cambio Climático, 2023).

Mexico has the potential to implement a new energy strategy, which would allow the country to grow as an application powerhouse for new and existing process areas. In addition, Mexico's participation in the international agenda should be broader, since it would need to collaborate with other countries to facilitate development and implementation (Palacios *et al.*, 2022).

◆◆ CONCLUSIONS

Hydrogen is an excellent source of energy due to its abundance on Earth. Its use offers several advantages, such as clean combustion, eliminating CO₂ emissions, operation in a closed and inexhaustible cycle. However, one of the great challenges that manufacturers face is safe storage. In general terms, to obtain hydrogen, an initial energy is required to break down the water or methane molecules and separate the hydrogen from the oxygen and carbon in these compounds. Water electrolysis can be used on an industrial scale to produce hydrogen, which requires efficient electrocatalysts. Its widespread use as a fuel depends on the optimization of the procedures where residual raw materials are used, and the process has a low environmental impact.

Fossil fuels are currently in high demand as renewable energy sources are transient. Hydrogen is a key piece for renewable energies to increase in demand because it is a carrier of clean energy. In the future, population growth and the

depletion of resources will lead to the search for options that adapt to the needs of the population, which is why hydrogen is bound to have a great impact on future generations. The environmental ramifications of a fossil-fuel-dependent lifestyle, particularly in terms of accelerated global warming, necessitate a shift towards cleaner and more sustainable energy alternatives. The rise in greenhouse gas emissions, primarily from burning fossil fuels, underscores the urgency for proactive measures by policymakers and researchers.

Mexico is in the process of transitioning towards a more sustainable and environmentally friendly energy model. Likewise, its government has a future projection with respect to clean energies because it promotes the reduction of greenhouse gases, reduces dependence on fossil fuels, and makes important investments in solar, wind, biogas, and biomass energy projects, among others, which encourage the private sector to develop them.

In this context, the concept of e-fuels, or electrofuels, stands out as a promising avenue to reduce emissions and transition away from fossil fuels. Among these alternatives, hydrogen emerges as a particularly versatile and clean energy resource, obtainable from various sources and production processes. Despite its current reliance on fossil fuels for production, the potential for hydrogen to be generated through renewable sources presents a transformative opportunity for economic growth. The "hydrogen economy" has garnered attention as a viable and advantageous option to deliver high-quality energy services efficiently and sustainably. Hydrogen's characteristics, including its lack of toxic emissions, high energy efficiency, and compatibility with electricity, position it as a transformative alternative for a sustainable global energy system. Its applications, from transportation to stationary fuel cells, make it a versatile solution.

Here, three experimental studies related to the effect of hydrogen on the behavior of flames were analyzed. In the first article, the burning of LPG at different percentages of hydrogen, under the OH-PLIF technique, is determined to ascertain its effects in relation to the equivalence

and improvement of oxygen in the distribution of the flame and reaction zone. Also, for a progress that benefits the reaction zone in the article, hydrogen is added to increase combustion and expand the flame. In the 90% LPG-H₂ IDF mixture, hydrogen enrichment does not demonstrate structure, which shows that a small percentage of LPG would slow down hydrogen combustion, where it is possible to determine the distribution and concentration of the hydroxyl within the flame and, consequently, appreciate an adequate behavior.

The second article highlights the higher speed of the fuel jet at the local extinction and restoration limit as a result of the addition of hydrogen. It was found that the energy required in the supply rate is decreased. Within a certain percentage range (30% - 90%), energy savings are achieved at both limits, but a complete extinguishing reduction effect is detected in a percentage range of less than 30% and, finally, in a range higher than 70%, an increase in fuel speed is required to restore the initial flame, where the stability of the flame is achieved in relation to the volumetric percentage of hydrogen and the Reynolds number.

Finally, according to the third article, the characteristics of heat emission and transfer in a flame mixed from LPG-H₂ between the percentages of 0% to 50% are highlighted, and therefore, a change in the appearance, emission of pollutants, and heat characteristics was found due to the addition of hydrogen. When the mixture is in a larger fraction of hydrogen, an increase in the temperature of the flame is discovered with a reduction of carbon dioxide and carbon monoxide emissions.

Acknowledgments

Z. P. Pérez-Urquieta and E. A. López-López express their gratitude to the UDLAP Honors Program for the support provided to carry out this research study.

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