Bachelor’s Thesis

Study of a gas turbine cycle with hydrogen combustion

under the supervision of

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by

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Statutory Declaration

This thesis is the result of my own work and includes nothing that is the outcome of work done in collaboration except as specified in the text.

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Vienna, June 2021

Signed by Álvaro de la Peña Pinteño on 06/28/2021 with a certificate issued by AC FNMT
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Abstract

As it is well known, electricity is an issue which plays an essential role in any society. However, the impacts its production provokes to the environment must be taken into consideration, mainly those due to greenhouse gases produced by burning carbon-containing compounds.

In this situation, a possible way of reducing these gases would consist in the production of electricity using hydrogen, which could also be produced by renewable sources.

Following this idea, this bachelor thesis will seek, through the compilation of different articles, research and previous work, to offer an analysis on how a pre-existing gas turbine cycle which works using natural gas as fuel could be implemented and transformed, to work with hydrogen.

Firstly, the properties of both fuels (natural gas and hydrogen) will be compared and assessed. Then, the effects that this change, in terms of fuel, causes in the turbo machinery of the cycle will be evaluated. Subsequently, I will discuss the settings required with the intention of minimizing possible losses in terms of performance or cycle efficiency.

After this point, this research will focus on another very important element in the face of this change: the combustion chamber. To begin, a comparison of the reactions that take place in it will be carried out, also explaining the particularities that the use of hydrogen as fuel has associated, later a comparison will be made between the different combustion systems that can be used, with the purpose to determine which will be the most appropriate for this element.

To conclude this research, a classification of the different, most prominent types of hydrogen which can be found today will be provided. Finally, some of the techniques which can be used to produce this hydrogen will be discussed.

Kurzfassung

Elektrizität ist bekanntlich ein Thema, das in jeder Gesellschaft eine wesentliche Rolle spielt. Allerdings müssen die Auswirkungen seiner Produktion auf die Umwelt berücksichtigt werden, die hauptsächlich auf die Treibhausgase zurückzuführen sind, die durch die Verbrennung kohlenstoffhaltiger Verbindungen entstehen.

Ein möglicher Weg, diese Gase zu reduzieren, bestünde in dieser Situation in der Stromerzeugung mit Wasserstoff, der auch aus erneuerbaren Quellen gewonnen werden könnte.

Dieser Idee folgend wird diese Bachelorarbeit versuchen, durch die Zusammenstellung verschiedener Artikel, Forschungen und bisheriger Arbeiten eine Analyse zu bieten, wie ein bereits bestehender Gasturbinenkreislauf, der mit Erdgas als Brennstoff arbeitet, implementiert und transformiert werden könnte, um zu funktionieren mit Wasserstoff.

Zunächst werden die Eigenschaften der beiden Gase (Erdgas und Wasserstoff) verglichen und bewertet, dann die Auswirkungen, die diese Änderung in Bezug auf den Brennstoff in der Turbomaschiner des Kreislaufs verursacht, bewertet und anschließend die erforderlichen Einstellungen mit den Absicht, mögliche Verluste in Bezug auf Leistung oder Zykluseffizienz zu minimieren.

Danach wird sich diese Forschung angesichts dieser Veränderung auf ein weiteres sehr wichtiges Element konzentrieren: die Brennkammer. Zunächst wird ein Vergleich der darin ablaufenden Reaktionen durchgeführt, wobei auch die Besonderheiten der Verwendung von Wasserstoff als Brennstoff erläutert werden, später ein Vergleich zwischen den verschiedenen einsetzbaren Verbrennungssystemen mit den Zweck zu bestimmen, welches für dieses Element am besten geeignet ist.

Zum Abschluss dieser Forschung wird eine Klassifizierung zwischen den verschiedenen bekanntesten Arten von Wasserstoff bereitgestellt, die heute gefunden werden können, und schließlich werden einige der Techniken diskutiert, mit denen wir diesen Wasserstoff herstellen können.

Resumen

Como es bien sabido, la electricidad actualmente es un elemento que juega un papel fundamental en cualquier sociedad, sin embargo, deben ser tenidos en cuenta los impactos que su producción generan sobre el medio ambiente, principalmente aquellos debidos a los gases de efecto invernadero que se producen al quemar compuestos que contienen carbono.

Ante esta situación, una posible medida que podría suponer una gran reducción de estos consistiría en la producción de esta electricidad usando hidrógeno, que a su vez podría ser producido con fuentes renovables.

Siguiendo esta línea de investigación, este trabajo de fin de grado pretenderá, mediante la recopilación de distintos artículos, investigaciones y trabajos previos, ofrecer un análisis sobre cómo podría implementarse y transformar un ciclo de turbina de gas preexistente, que funciona empleando gas natural como combustible, a uno que use hidrógeno.

En primer lugar, se realiza una comparación entre las propiedades de ambos elementos (hidrogeno y gas natural), posteriormente se evaluarán los efectos que este cambio en cuanto al combustible provoca en la turbo maquinaría del ciclo, debatiendo posteriormente los ajustes a realizar con la intención de minimizar las posibles pérdidas en cuando a las prestaciones o la eficiencia del ciclo.

Tras este punto, esta investigación se centrará en otro elemento muy destacado frente a este cambio: la cámara de combustión. Para comenzar, sobre ella se realizará una comparativa de las reacciones que allí se producen, y sobre las particularidades que el uso de hidrogeno como combustible tiene asociado, posteriormente se realizará una comparativa entre los distintos sistemas de combustión que pueden ser empleados, con la finalidad de determinar cuál será el más apropiado para este elemento.

Para concluir esta investigación, se ofrece una breve clasificación con los distintos tipos de hidrógenos más destacados que se pueden encontrar actualmente para finalmente comentar posibles métodos a partir de los cuales puede ser producido este elemento.

Resum

Com és ben sabut, l'electricitat actualment és un element que juga un paper fonamental en qualsevol societat, no obstant això, han de ser tinguts en compte els impactes que la seua producció generen sobre el medi ambient, principalment aquells deguts als gasos d'efecte d'hivernacle que es produeixen en cremar compostos que contenen carboni.

Davant aquesta situació, una possible mesura que podria suposar una gran reducció d'aquests consistiria en la producció d'aquesta electricitat usant hidrogen, que al seu torn podria ser produït amb fonts renovables.

Seguint aquesta línia d'investigació, aquest treball de fi de grau pretendrà, mitjançant la recopilació de diferents articles, investigacions i treballs previs, oferir una anàlisi sobre com podria implementar-se i transformar un cicle de turbina de gas preexistent, que funciona emprant gas natural com a combustible, a un que use hidrogen.

En primer lloc, es realitza una comparació entre les propietats de tots dos combustibles(hidrogen i gas natural), posteriorment s'avaluaran els efectes que aquest canvi quant al combustible provoca en la turbo maquinària del cicle, debatent posteriorment els ajustos a realitzar amb la intenció de minimitzar les possibles pèrdues en quan a les prestacions o l'eficiència del cicle.

Després d'aquest punt, aquesta investigació es centrarà en un altre element molt destacat enfront d'aquest canvi: la cambra de combustió. Per a començar, sobre ella es realitzarà una comparativa de les reaccions que allí es produeixen, i sobre les particularitats que l'ús d'hidrogen com a combustible té associat, posteriorment es realitzarà una comparativa entre els diferents sistemes de combustió que poden ser emprats, amb la finalitat de determinar quin serà el més apropiat per a aquest element.

Per a concloure aquesta investigació, s'ofereix una breu classificació amb els diferents tipus d'hidrògens més destacats que es poden trobar actualment per a finalment comentar possibles mètodes a partir dels quals pot ser produït aquest element.

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Nomenclature

Abbreviation	**Description**
NG	Natural gas
NO$_x$	Nitric oxides
W$_c$	Work of the compressor
SFT	Stoichiometric flame temperature
LDI	Lean direct injection

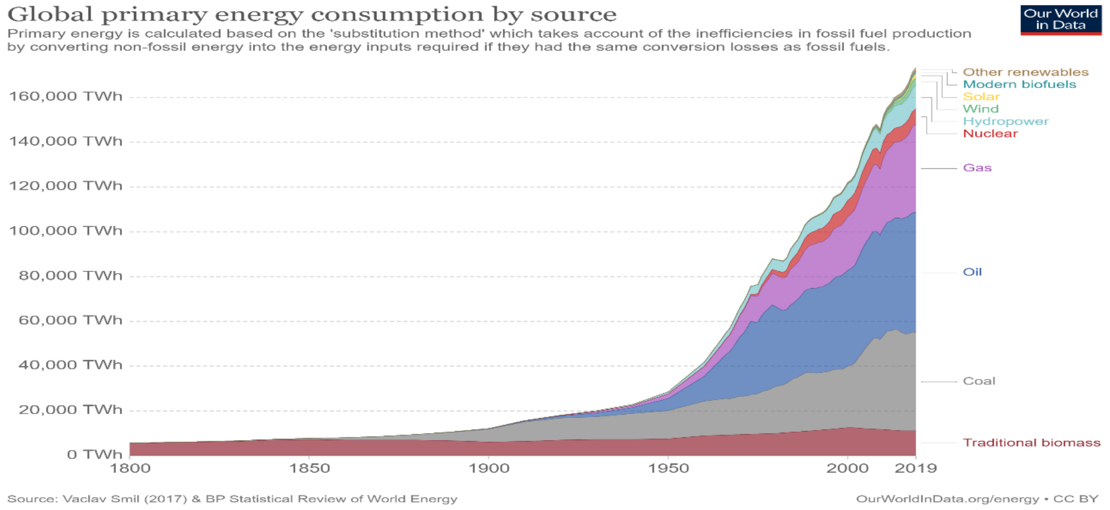
1.- Introduction

Nowadays, energy plays an essential role in modern societies, it could be considered as an essential issue for economic growth and the improvement of our well-being. It is the angular stone of any industrial, manufacturing or production process, being fundamental for the development of any region or county. Consequently, whenever a country undergoes a process of economic growth, it will be alongside an increase in energy consumption, as is shown in Figure 1.

Therefore, worldwide energy consumption and its production has been constantly and gradually rising, except for a lower growth in the years 2009 and 2020. These two years experienced a decrease in economic growth due to an economical and sanitary crisis, respectively, as can be seen in Figure 1.

This mentioned energy comes from a variety of sources, we can distinguish two opposite groups: on the one hand we have the non-renewable resources, their use and exploitation provoke polluting emissions, they are mainly those denominated as fossil fuels (coal, oil and natural gas). On the other hand, we can find renewable sources. These have a low impact for the environment, causing less pollution. Their main disadvantage is their dependence on nature's behaviour. Within this group, solar, wind and hydroelectric energy stand out. These systems cannot be used for the whole day due to the lack of sunrays at night or the noncontinuous of the wind.

However, the facilities that use high-capacity power systems demand energy during the whole day, to face this situation we can find two choices. The first choice consists of the use of an energy storage system like batteries.



Global primary energy consumption by source

Primary energy is calculated based on the 'substitution method' which takes account of the inefficiencies in fossil fuel production by converting non-fossil energy into the energy inputs required if they had the same conversion losses as fossil fuels.

Source: Vaclav Smil (2017) & BP Statistical Review of World Energy

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Figure 1 Global primary energy consumption by source.(Iea Org, 2021).

However, batteries are very expensive and have significant adverse effects on the environment due to the use of highly polluting mines inside. The other alternative would be the employment of a renewable energy source which could be used with independence of the climatology agents. That could be the case of hydrogen, produced via renewable energy sources and used as fuel.(Koç et al., 2020).

As seen in the Figure 1, traditional biomass is an energy source that has remained practically constant since the XIX century. From the middle of the same century and motivated by the second industrial revolution, we can observe the development of coal and oil as energy sources, being at this moment the most important sources of energy, providing us with approximately 55% of the energy consumed in the year 2019, they are used as fuel in vehicles and in many heavy-duty electricity productions plants. Beginning in the 50s, a quick development in the use of natural gas as source of energy takes place. This gas is mainly used in heavy-duty turbines as a fuel, being at this moment one of the most important production system of electricity to supply cities and countries. To conclude the analysis of this plot, in the last year we can observe the increase of the use of renewable sources as energy sources. This is a fundamental point to reduce our pollution levels and end the emission of greenhouse gases.

This thesis will focus on the changes required to use these power plants with hydrogen as fuel, what will mean a giant step in the reduction of global pollution, being the right direction to achieve the Paris agreement's goals with the aim to reverse the current climate change situation.

This natural gas is used, in many cases, as fuel to produce electricity in a gas turbine cycle, those are based on the Rankine cycle. The simplest consists in four steps (illustrated in Figure 2), firstly the air enters the cycle at ambient pressure and temperature. Then it will go through the compressor, it can have different shapes mainly axial (if the air flow is parallel to the axis of the compressor) but also the flow can be radial (if the flow has a certain angle with the axis). We use work (W_C) to increase the pressure of the gas, ideally this process should be an isentropic compression (1->2s). Depending on the efficiency of the compressor, the compression will more closely resemble an isentropic or not.

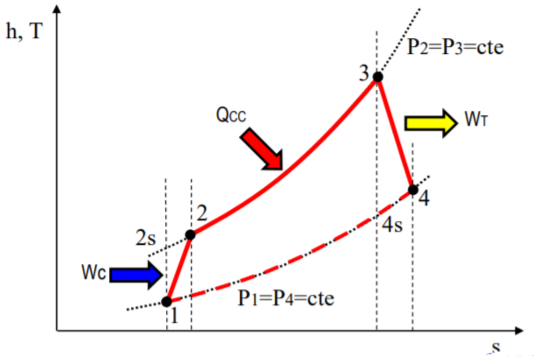


Figure 2 Representation of a Brayton cycle with its more significant points.(ARREGLE et al., 2002)

After this step, the air flow goes to the combustion chamber, there, at constant pressure, the combustion takes place (in Figure 1 shown as line 2->3), these exhausted gases go to the turbine, where we can find an expansion in different steps depending on the number of row blades of the turbine, from there we get the energy to supply the demand.

This is the simplest cycle, there are, nonetheless many variations. We can, for instance, include a regenerator to improve the global efficiency, two or three steps in the process of compression, some turbines with different steps of combustion can also be combined. In any case, they are derivatives of the Brayton cycle described previously and have the purpose to reduce the energy needed to contribute to the cycle and maximize the energy we get.

One of the most outstanding characteristics of the gas turbine cycle is the easy regulation it provides. We can quickly change the electricity it supplies according to the variations in the demand. It should also be mentioned that it has less elements than the steam power cycle and it is smaller. Thus it offers us a wide variety of implementation: we can find from small turbines called microturbines which are able to generate from 20 to 350 kW to heavy industrial turbines able to supply up to 350 MW and with an efficiency around 40%, including as well those used in the aerospace industry for the transport of goods and passengers, they have less power but a higher efficiency (up to 45%) due to a higher development and optimization of the material used.

NG is mainly composed of methane (CH_4) and nitrogen. During its combustion, it releases substances to the environment, when those emissions interact within an ecosystem, they demand some source of material or energy resource within said ecosystem; some of these sources are water, oxygen, solar energy and biological systems as described by (Díaz & Ascencio, 2009). Despite the greenhouse emissions due to its content in carbon, NG also produces other contaminants during its combustion. When increasing the combustion temperature, the process of nitrogen oxides formation will be more likely (since an increase in temperature reaction is reflected in an increase in the constant equilibrium of the NO_x formation process). This increase of NO formation will grow parabolic with temperature. On the other hand, NO_2 formation presents the same trend, (however, the amount of NO_2 produced it will be almost 10,000 times less than the NO produced) (Díaz & Ascencio, 2009).

The last contaminant to have into consideration is SO_x, its production depends on the entrance temperature of the gases in the turbine SO_x are unstable and react quickly with water in the air producing hyposulphurous acid. This causes an acid deposition known as acid rain, which can seriously affect the plant cover, they are also the cause of the degradation of a wide range of materials.

After this brief introduction about the consumption, supply and generation of energy, this bachelor thesis will address and discuss some topics related to this aspect of the engineering, specially related to the transformation of energy from the primary sources so it can be used for the human needs. Firstly, the benefits and disadvantages of using a heavy-duty gas turbine with hydrogen as fuel or with natural gas will be shown, paying special attention to the performances of each kind of machine and the environmental impact each one may have. Then will be explained if an existing heavy-duty gas turbine could be used with hydrogen combustion, explaining if would be completely incompatible, or otherwise, the requirements or modifications any component would need.

Another aspect to deal with will be the combustion chamber, it is one of the more outstanding components of the power cycle in this transformation. The changes it will face to be able to work with hydrogen will be discussed, explaining the chemical reaction which will take place there, the size or shape it would have and the different methods we will implement to minimize the production of NO_x gases. The next point of this thesis will be focussed on the benefits of hydrogen, such as the reduction of pollution it is associated with. The main part of this thesis will end with a brief discussion and comparation between some of the actual methods that can be used to get the hydrogen.

This research will conclude with a summary of the arguments and issues previously covered and trying to foretell the next steps into the development and implementation of this technology.

2.- Moving from natural gas to hydrogen

2.1 Hydrogen compared to natural gas.

When we want to change the fuel supply of a turbine power cycle from natural gas to hydrogen, should be taken and assessed the differences of each compound, evaluating their potential benefits or disadvantages, should also be analysed the performances of the whole cycle focusing also on each of its components.

Firstly, the differences between natural gas and hydrogen must the discussed. On the one hand, NG is composed of different elements but it is methane in approximately 95% (UnionGas, 2017). On the other hand, hydrogen is one of the simplest elements, just integrated by one proton and one electron. It is really abundant on earth but mostly mixed with oxygen or carbon, not in its pure form, what means we cannot use it directly to our needs, it requires its production and purification (some methods will be briefly explained at the end of this research). Naturally, those processes require money and energy. However, it is also a storable element. Once it is produced, it can be stored at a low pressure as many other similar gases used for industrial processes being ready to use when it is necessary, it can also be transported by hydrogen pipelines (similar to NG) or even by train. One of the properties which stands out from hydrogen is the high energy it contains per mass, with a value of approximately 120MJ/kg compared to the NG (50 MJ/kg) however, it one of the lightest gases known so it has a poor rate of energy per volume (10 MJ/Nm^3).

When it burns, the flame is colorless. Due to its higher energy, hydrogen can achieve higher temperatures. The approximately flame temperature for a mix of 19.6% in volume of hydrogen is 2321K (Badía, 2005). The speed of propagation of the flame, 2.65 m/s, being approximately six and a half time higher than the speed of the methane, this favors a possible explosion, while diffusivity and density tend to reduce its probability, especially in opened spaces. In closed spaces, the hydrogen escape takes place with decreased temperature which reduces the risk. On the other hand, chemical reaction proceeds with volume reduction, so instead of an explosion what happens is an implosion (Gutierrez Jodral, 1968). This issue will be addressed in the next chapter.

Other difference that must be said is the diffusion coefficient of both fuels. This coefficient represents the ease with which each solute moves in a given solvent, in this case air, for the methane it has a value of 0,18 cm^2/s. However, in the case of the hydrogen it reaches a value of 0,61 cm^2/s (nearly three and a half times higher). This property makes sense according to the flame speed propagation discussed previously.

Hydrogen combustion is a topic which is nowadays under development and investigation. Nevertheless, a limiting factor with those tests is the actual availability of hydrogen. Tests lasting around an hour can burn through the available stored hydrogen, which can take up to a week to replenish This is a significant logistic challenge because large quantities of hydrogen gas are needed, but there is not large-scale production yet (Filn, 2019). In the table which follows we can see a summary of the differences between the technical properties from both of fuels discussed.

Property	Hydrogen (H_2)	Methane (CH_4)
Calorific power (MJ/kg)	120	50
Autoignition temperature (ºC)	585	540
Adiabatic flame temperature in the air (ºC)	2,045	1,875
Ignition limit of ignition on air (% vol.)	4-75	5,3-15
Flame speed propagation (m/s)	2,65	0,4
Diffusion coefficient in air (cm^2/s)	0,61	0,18
Toxicity	No	No

Table 1 Comparation of properties between hydrogen and methane.

The most outstanding characteristic from hydrogen and the reason behind its interest in the industrial processes is due to its combustion, which does not produce any kind of greenhouse gases. Hence, it becomes really interesting fuel to use to produce electricity, like in a gas turbine cycle, or even as fuel for vehicles. The emissions that should be taken into consideration due to its high temperature of the flame are the production of NO$_x$. In the next chapter will be discussed some methods to try to minimize them.

2.2 Effects on turbomachinery

Due to the differences with natural gas exposed previously, the use of hydrogen combustion has many implications on the turbomachinery (compressor and turbine). The combustion chamber will be discussed in the next chapter.

The most relevant implications that will be assessed and discussed are mainly: a) variation of the enthalpy drop in the expansion, b) a variation of the flow rate at the turbine inlet which, in turn, affects the turbine/compressor matching, c) a variation of the heat-transfer coefficient on the outer side of the turbine blades, affecting the cooling system performances (Chiesa et al., 2005) d) the sealing of the system because the H_2 molecules have a greater tendency to leak than other gases because they are smaller so is easier to squeeze through small cracks, gaps and other tolerances that cannot accommodate a larger CH_4 molecule (Noble et al., 2021).

Combined with the hydrogen flow, we can find a specific proportion of steam or N_2, these substances are added with the aim to control the NO_x production, as I will be discussed in the next chapter.

As it can be seen in the chart of Figure 3, we can observe the influence of hydrogen combustion, combined with steam in the isentropic enthalpy drop in given conditions, compared to natural gas. The enthalpy drop in its minimum level is around 5%, without the presence of steam. This drop is motivated firstly due to the variation on the specific heat and secondly because of the variation of the temperature drop in the expansion of the gas in the turbine, as the chart shows when we start adding steam. This enthalpy drop gradually increases reaching around 13% when the diluent to H_2 mass ratio is 8, simultaneously increasing the mixture of steam carries to an improvement in the specific heat of the mix, causing a decrease in temperature drop,

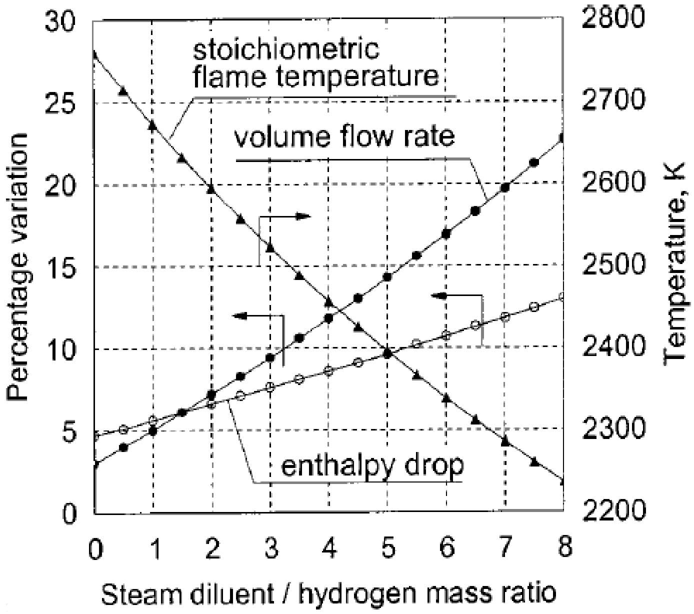


Figure 3 Variation of the stoichiometric flame temperature and of the inlet volume flow rate and isentropic enthalpy drop of a hydrogen and steam fueled gas turbine with respect to the reference natural gas case.(Chiesa et al., 2005).

this motivates an increase in the outlet temperature of the turbine. Lastly, it should be mentioned that despite the lack of additional steam, the volume gas flow of the hydrogen increases around 3% when compared to the natural gas.

Analysing Figure 4, we can observe some similitudes and differences. In this case, the addition of nitrogen hardly causes a variation of the enthalpy drop which remains constant at 5%. Another fact to highlight is related to the stoichiometric flame temperature, while adding steam we need a rate of diluent over hydrogen mass of around 3.5 to get a temperature of nearly 2500K in the case of nitrogen. This rate increases up to 8, nearly the double, due to the specific heat of the steam nearly the double of the nitrogen (1.04 J·g^{-1}·K^{-}1 for nitrogen and 2.01 for the steam).

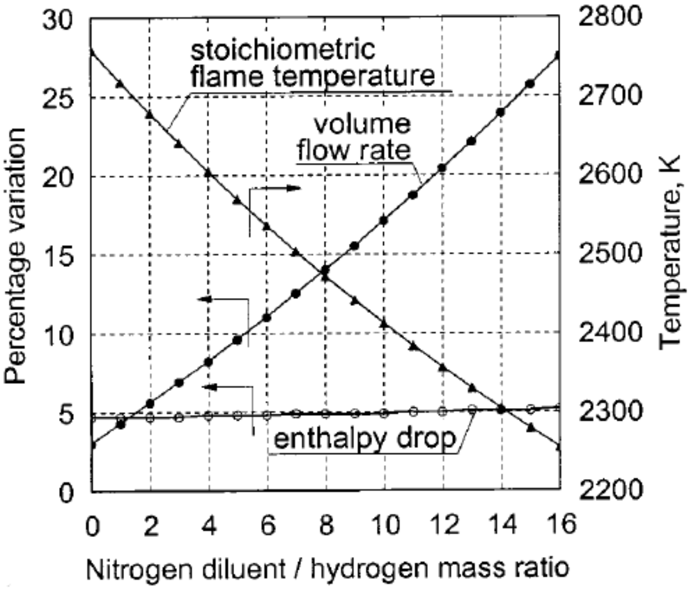


Figure 4 Variation of the stoichiometric flame temperature and of the inlet volume flow rate and isentropic enthalpy drop of a hydrogen and nitrogen fueled gas turbine with respect to the reference natural gas case.(Chiesa et al., 2005).

The second implication to be assessed would be the relation between the compressor and the turbine, due to the variation of the fuel used and its changes into the flow rates, the designed working point should be reevaluated to achieve the equilibrium between both machines, according to research (Chiesa et al., 2005), we can find three methods to fix this situation.

The first one keeps the compressor in the same working point as with natural gas and reduces the inlet temperature to the turbine to match again, it will provoke a reduction into the pressure ratio in the turbine, this solution would be the most damaging for the cycle performances because the energy obtained from a Brayton cycle is mainly based on the temperature of the flow at the entrance of the turbine. Therefore, this system would not be implemented.

The second possible solution consists in leaving the variable guide vanes of the compressor in the same angle and establish the same temperature at the entrance of the turbine and regulate the gas flow adjusting the pressure ratio of the compressor. This solution would increase the compressor and turbine working ratio to reduce the mass flow and allow the matching between both elements.

The third and last solution is based on leaving the temperature at the entrance of the turbine and the pressure working ratio at the same point as they were working previously with natural gas and on the other hand reduce the mass flow by moving and adjusting the variable guide vanes of the compressor to reduce the gas flow along the cycle.

It should also be mentioned that these three methods mentioned are compatible and combinable but, as it has been said, the first one would not be excessively interesting from an energetic point of view.

The third issue to be addressed according to (Chiesa et al., 2005) is the cooling of the blades of the turbine. They are one of the most sensitive part of the cycle, specially the first row, because they must deal with the mass flow when it reaches its higher temperature just after the combustion chamber, so it is essential to give them a good cooling. Blades can be considered as a crossflow heat exchanges where the cooling system has to ensure that the temperature of the material never reaches a value which can produce any damage to the material.

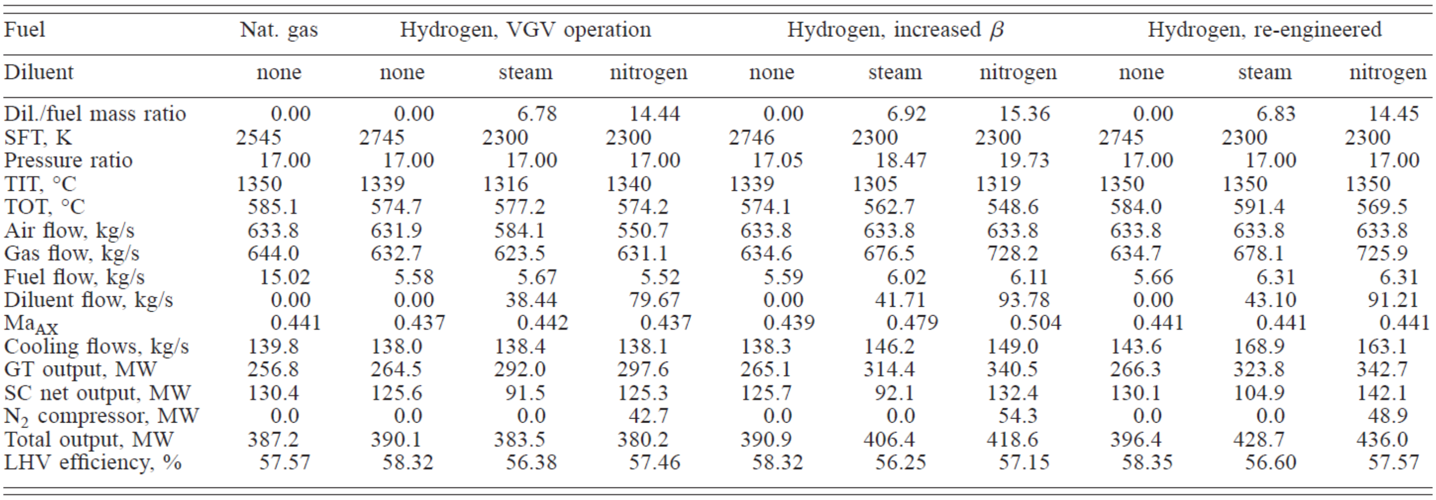
Nowadays, many methods to accomplish this task can be found. Most of these are based on an air flow which circulates by many channels inside the blades. We can find some where the air circulates parallel to those channels or some improvements, with systems where the air impacts with the inside face of the blade or even some where the air circulates inside the blade but goes out by many small holes, creating a protective wrap along the external face.

There are also few systems which use water at high pressure as refrigerant, its main advantage is its higher specific heat so it will provide a better cooling to the blades, but otherwise it supposes a huge increase into the weight of the turbine.

In the aspect of cooling, changing to a hydrogen combustion has two implications, on the one hand, the new elements of the mass flow have a higher convective heat transfer coefficient. This implies a higher heat transfer between the flow and the external face of the blades, hurting its thermal equilibrium. On the other hand, the second implication, is motivated because of the increase into the pressure ratio, this fact provokes the increase into the convective heat transfer coefficient both in the external and internal faces of the blade because of the fluid density increase, this effect decreases the cooling performances of the air inside the blades.

To face these two consequences, we can distinguish between two solutions. The first one could be to increase the cooling system flow. This would imply the redesign of the blades of the turbine, this solution would not be recommended, because the aim of this thesis is moving from a cycle based on natural gas combustion to one with hydrogen with the minimum changes into the original cycle and this would imply big changes for the design and manufacturing process with large economic implications.

On the other hand, another solution could be suggested: to decrease the temperature of the mass flow at the entrance of the turbine, even though it implies the reduction of the power performances. Still, it seems to be the solution with lower impact into the turbine original design.



Fuel	Nat. gas	Hydrogen, VGV operation			Hydrogen, increased β			Hydrogen, re-engineered		
Diluent	none	none	steam	nitrogen	none	steam	nitrogen	none	steam	nitrogen
Dil./fuel mass ratio	0.00	0.00	6.78	14.44	0.00	6.92	15.36	0.00	6.83	14.45
SFT, K	2545	2745	2300	2300	2746	2300	2300	2745	2300	2300
Pressure ratio	17.00	17.00	17.00	17.00	17.05	18.47	19.73	17.00	17.00	17.00
TIT, °C	1350	1339	1316	1340	1339	1305	1319	1350	1350	1350
TOT, °C	585.1	574.7	577.2	574.2	574.1	562.7	548.6	584.0	591.4	569.5
Air flow, kg/s	633.8	631.9	584.1	550.7	633.8	633.8	633.8	633.8	633.8	633.8
Gas flow, kg/s	644.0	632.7	623.5	631.1	634.6	676.5	728.2	634.7	678.1	725.9
Fuel flow, kg/s	15.02	5.58	5.67	5.52	5.59	6.02	6.11	5.66	6.31	6.31
Diluent flow, kg/s	0.00	0.00	38.44	79.67	0.00	41.71	93.78	0.00	43.10	91.21
Ma_{AX}	0.441	0.437	0.442	0.437	0.439	0.479	0.504	0.441	0.441	0.441
Cooling flows, kg/s	139.8	138.0	138.4	138.1	138.3	146.2	149.0	143.6	168.9	163.1
GT output, MW	256.8	264.5	292.0	297.6	265.1	314.4	340.5	266.3	323.8	342.7
SC net output, MW	130.4	125.6	91.5	125.3	125.7	92.1	132.4	130.1	104.9	142.1
N_2 compressor, MW	0.0	0.0	0.0	42.7	0.0	0.0	54.3	0.0	0.0	48.9
Total output, MW	387.2	390.1	383.5	380.2	390.9	406.4	418.6	396.4	428.7	436.0
LHV efficiency, %	57.57	58.32	56.38	57.46	58.32	56.25	57.15	58.35	56.60	57.57

Table 2 Comparison of the results for each of the solutions implemented.(Chiesa et al., 2005).

In Table 2 we can find the results from the simulation carried out by Chiesa et al. (2005). This table contains the results from the simulations in which the three solutions discussed previously were tested. For every case, we can find the results using just hydrogen or hydrogen combined with steam or nitrogen. On the left hand, we can firstly find a column which correspond to the data from the original turbine cycle based on natural gas combustion. It will be used as reference to see its original performances.

Moving to the results of the first simulation (variating the variable guide vanes and keeping the pressure ratio constant, in this case at 17), when the hydrogen does not content any diluent, it provides by far the largest stoichiometric flame temperature, with also a small increase in the power provided by the turbine with respect to the natural gas. It also provides the highest efficiency rate (58.32%).

However, due to the large flame temperature and the formation of NO_x emissions, we should mix steam or nitrogen with this hydrogen. With the addition of steam, we have to reduce the air flow (to leave space for the addition of the steam) The improvement of some of the performances, mainly in the gas turbine output, achieving 293 MW, can also be seen, motivated by the reduction in the consumption of the compressor due to the lower air flow. There is, as well, an increase in the enthalpy drop. Nonetheless, this does not imply a significant change in the total output of the cycle. Lastly, it should be mentioned that the efficiency decreases in nearly one point regarding the cycle with natural gas.

In the case of nitrogen, the inlet temperature is really similar to the case of hydrogen. We can observe a larger reduction in the air flow, because, of the higher diluent fuel mass ratio. Thus, we also need energy to compress this nitrogen, the efficiency for this case remains practically constant as in the original cycle.

The second column belongs to the result in which the compressor ratio is increased to keep the air flow constant. We can observe similar results as in the previous example. For this case, we need a higher amount of diluent, so the ratio of nitrogen or steam is larger. The addition of nitrogen requires a higher pressure than the steam, we can also observe a clear reduction in the inlet temperature, probably as a result of the increase in the cooling mass flow. This decrease provokes a reduction in the turbine performances and efficiency. Otherwise, the power provided by the turbine is higher than previously, because the air flow circulating along the turbine is around 8.5% higher in the case of steam and 15% larger in the case of nitrogen as additive.

The last columns of the table show the results with a redesigned engine. In general terms, for this case we obtain some improvements mainly with regard to the power provided by the turbine and also a higher value for the efficiency compared to the other cases but is not the aim of this research to redesign a new engine.

According to the results provided by this simulation (Chiesa et al., 2005), in which the implications of moving from a traditional NG to a hydrogen combustion and their possible solutions to minimize its impact on the turbomachinery have been assessed, we can conclude that from a technical view, it would be possible to use a pre-existing gas turbine cycle and with the setting of some parameters, use it with hydrogen.

Both solutions assessed would be appropriate for this task but would be recommended the first solution: adjust of the variable guide vanes of the compressor, to adequate the mass flow along the circuit allowing the matching between the compressor and the turbine, combined with a reduction of the temperature at the entrance of the turbine to preserve the health of specially the first turbine blade row and avoid its damage. This solution would be preferred to the second one, because it requires a lower impact on the original cycle, simply the modification of the vanes, elements which are already included in the compressor. Otherwise, the rise of the compressor ratio, proposed as solution two, requires larger mechanical modifications as a larger compressor with a bigger generator.

Despite the fact that in these cases we have obtained an efficiency of nearly 57%, it is because it has been analyzed with simplest Brayton cycle but including some modifications as different steps for compression or expansion or reheat to reduce the energy supplied by the chamber. This efficiency could be improved, according to (Bannister et al., 1997), who also studied the use of hydrogen as fuel, but in this case for a Rankine cycle based on water and steam and used for the production of energy, which includes regeneration and reheat, it has provided an efficiency of the cycle of around 71%, which is a really high value.

The last issue of the turbine to be taken into consideration is its sealing. At high temperature and pressure ratio, increased leakage can become a serious performance penalty, especially in the turbine section (Fadok & Diakunchak, 2008). This aspect can be easily fixed by using a special coating or a bondcoat to prevent the leaks. This would be an easy and effective solution which would not imply any penalty in the performances of the cycle.

3.- Process of combustion

3.1 Chemical reaction and implications

In both cases, the purpose is to obtain the energy storaged using oxygen to produce its combustion. These are the formulations of the reactions:

$$\mathrm{CH_4} + 2\mathrm{O_2} \text{—}> \ \mathrm{CO_2} + 2\mathrm{H_2O} \qquad (1)$$

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \text{—}> \ \mathrm{H_2O} \qquad (2)$$

Obviously, both are exothermic reactions, but due to the characteristics of each fuel they have some differences: the first one comes up by just observing the formulation of the reactions. The combustion of hydrogen does not produce any carbon emission, preserving the earth from greenhouse pollution.

The second difference, and among the most important one, is the high-speed flame of hydrogen. It is nearly an order of magnitude higher than in the case of the NG. In general terms, using the same conditions, a premixed, dry low NO_x nozzle would need 10 times higher flow velocity to prevent the flame from flashing back and damaging the hardware (Noble et al., 2021).

The third difference is about the higher adiabatic flame that hydrogen achieves in its combustion. It is somewhere in between 5 to 10% higher than when using NG (Noble et al., 2021). This property has two implications: the first one involves the increase in the potential production of $\mathrm{NO_x}$emissions (implication which will be addressed in the next point) and the second one is about the potential damaging or deterioration of the mechanic components of the machinery. Another difference between these two combustions is the difference in the flame geometry. Hydrogen flames are highly thermo-diffusively unstable, creating corrugations and wrinkles along the flame that will grow, becoming bigger. This is a fact that also increases its flame speed.

Theoretically, according to the higher heating value (120 MJ/kg for the hydrogen and 50 MJ/kg for NG), the gas flow required for hydrogen to produce the same energy would be nearly half than when compared to the case of NG. Otherwise, hydrogen is, at the same conditions (temperature and pressure), eight times less dense than the NG. Therefore, its volumetric lower heating value is roughly a third of CH_4 (Noble et al., 2021). This will provoke that the gas turbine based on hydrogen combustion will require three times more volume than when it was previously working with NG. A suggested way to solve this issue would be by supplying H_2 at a higher pressure. Nevertheless, it would imply a rise into the operation costs of the cycle.

Combustion instabilities, also called as combustion dynamics, should be considered as well. In the case of hydrogen combustion, the combustion instability phenomenon has the challenging feature that its characteristics are nonmonotonic with operating parameters (such as combustor inlet pressure, combustor inlet temperature, fuel gas composition, etc.(Noble et al., 2021). Consequently, it is difficult to predict the increment in combustion dynamics due to the addition of H_2, so different scenarios should be assessed.

These properties and differences discussed in this section related to the combustion make a move from a traditional NG gas combustion to hydrogen incredibly challenging. Therefore, some changes in the previous working parameter to ensure the life of the machinery and obtain an appropriate performance to make this process technically, energetically and economically viable should be carried out.

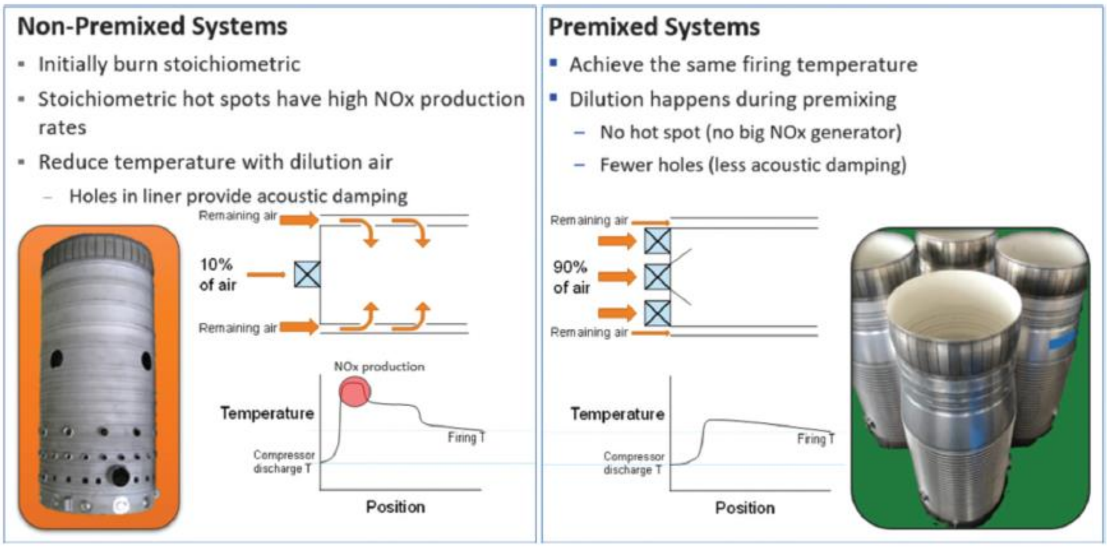
3.2 Diffusive compared to premixed combustion

As a brief introduction, in the context of deflagrations, we can find two types. Firstly, we can find the premixed flames. They are flames whose liberation heat zone is located in the flame front. The temperature increases along the axial position, starting in the bottom of the flame and achieving its tops in the front. They stand out because the mix of the components which intervene in the combustion is developed previous to the combustion. This is the way to control its temperature. In these flames we can distinguish three zones. The first one, called the pre-heat zone. There we can find low exothermic reactions, as the components do not have enough temperature to react yet. Then, we can find the reaction zone, it is the main part of the combustion. Once the components have reached a concrete temperature, the combustion takes place. This is where the heat is released. Finally, we can find the post-reaction zone, where the gases from the combustion get cool.

The speed of this combustion can be modified by different factors, one of the most important is the oxidant element and its proportion with respect to the fuel. An increase in the proportion of oxygen will rise the combustion speed. The initial temperature of the components is another factor. The higher the starting temperature, the higher the growth in the flame speed. A larger range of flame temperatures can be reached with this burning system and modifying those parameters.

On the other hand, we can find the laminar flames. In these kinds of flames, the mix of the components does not take place before the reaction. They mix at the same time they are burning. Another characteristic to highlight is that the temperature this system achieves is practically the stoichiometric.

This combustion system requires a complex study but one of the most accurate description was made by Michael Faraday in 1908. He analysed the flame of a candle, dividing the flame in three parts. The intern zone, composed of the exhausted gases, which are gases which cannot get burned. Then, one finds goes the intermedia zone, located in the limit where the fuel starts mixing with surround oxygen, allowing its combustion. This is the region with higher temperature so it emits light. The third region is composed by the external zone, mainly integrated by oxygen. Here the free radicals formed in the areas of higher temperature combine with oxygen, completing the oxidation or escaping in the form of soot.



Non-Premixed Systems

- Initially burn stoichiometric
- Stoichiometric hot spots have high NOx production rates
- Reduce temperature with dilution air
  - Holes in liner provide acoustic damping

Premixed Systems

- Achieve the same firing temperature
- Dilution happens during premixing
  - No hot spot (no big NOx generator)
  - Fewer holes (less acoustic damping)

Figure 5 Some differences from premixed and non-premixed systems (Noble et al., 2021).

With independence of the kind of combustion, any burning system must guarantee a certain margin of regulation. It is basically the maximum and minimum power that the burner is able to produce before the appearance of instabilities and incomplete combustion. The stability that each burner can provide, understood as the ability to keep the combustion outside the designed conditions should be assessed, as well as the polluting emissions it produces.

3.3 Performance and emissions

In this chapter, will be employed hydrogen with the combustion systems exposed previously with the intention to get an appropriate balance between the performances and the emissions from the power cycle. As has been said, in diffusive flame combustors, the temperature of the flame nearly achieves stoichiometric conditions, due to its high value it should be reduced by incorporating some diluents, like nitrogen or steam. However, the addition of any of those provokes a reduction into the performance and efficiency of the cycle, as has been exposed previously.

On the other hand, we can find the premixed burners, they offer the possibility to regulate the flame temperature variating the oxygen of the mix. This option also involves its risks because realizing a stable premixed hydrogen flame is not straightforward due to its high flame speed, it demands high air velocities to obtain short mixing times and high turbulence rates. As another drawback, premixed combustors may suffer from high pressure drops.

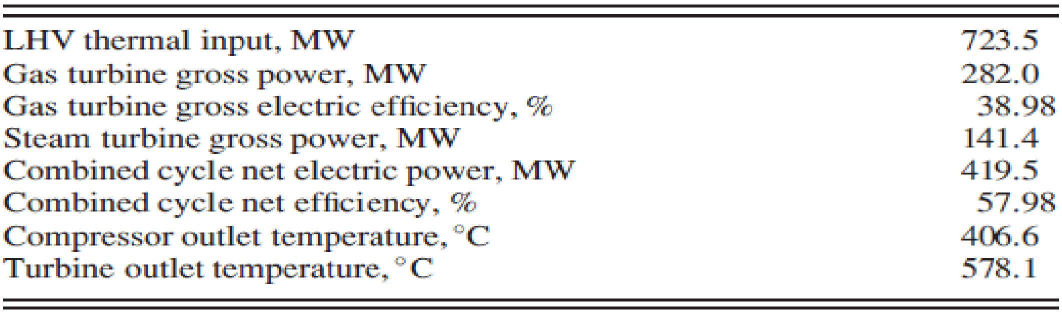
For this reason, gas turbine manufacturers are currently investigating and developing different combustor geometries in order to obtain the same NO_x emissions and combustor pressure drops achieved in natural gas–fueled combustors. The current industrial practice to burn H_2 in a gas turbine consists of employing diffusive flame combustors and prevent NO_x formation by diluting the fuel with steam or nitrogen which could be got from the steam cycle or an air separation unit, respectively (Gazzani et al., 2014).

According to (Gazzani et al., 2014), the use of fuel dilution decreases the efficiency due to different reasons: if nitrogen is used, it requires a compressor to rise the pressure from the air separation unit (where we get the nitrogen from) until the minimum combustor inlet pressure, this provokes an obvious rise into the economic costs and a decrease into the net plant efficiency because this compressor needs electricity to work. Should be mentioned that this discharge pressure must be a little higher because combustors may require a fuel injection pressure higher than the air pressure.

On the other hand, if we use steam and it is extracted from the heat recovery of the cycle, we will also penalize the plant global efficiency due to the energetic loss of mixing the steam with the fuel but also because of the reduction of the temperature at the entrance of the turbine, necessary to deal with the higher content of H_2O in the fuel gases. Another disadvantage of the employment of this diluent is the rise into the heat transfer coefficient, motivating an increase into the temperature of the turbine blades. Therefore, the cooling system should be modified to minimize this excess of heat or the temperature at the entrance should be reduced (also reducing the outpower), but otherwise the blades of the turbine may be damaged.

Must be also mentioned that every year the targets and regulations about polluting emissions are becoming stricter, being really challenging to achieve with the use of diluents in a diffusive flame.

Those reasons are why the actual industry is trying to develop premixed hydrogen combustors. However, due to the special characteristics of the hydrogen exposed before, this system of combustion should take into consideration different issues: the larger flammability of the hydrogen and its lower ignition temperatures, makes harder the task of mixing the air with the fuel without provoking the autoignition, the higher flame speed provokes an unstable combustion being able to produce a flashback which would damage the burners. These burners may have a different geometry to limit the pressure drop with this kind of combustion system is mandatory to achieve a perfect mixing of the air and fuel before the combustion to control the emissions of NO_x.



LHV thermal input, MW	723.5
Gas turbine gross power, MW	282.0
Gas turbine gross electric efficiency, %	38.98
Steam turbine gross power, MW	141.4
Combined cycle net electric power, MW	419.5
Combined cycle net efficiency, %	57.98
Compressor outlet temperature, °C	406.6
Turbine outlet temperature, °C	578.1

Table 3 Performances and characteristics of the original power cycle used as reference, with NG as fuel. (Gazzani et al., 2014).

With the aim to compare the performances obtained by the different systems of combustion, will be discussed the results from the simulation developed by (Gazzani et al., 2014). In Table 3, we can see the heat balance and performances of a gas turbine cycle used as reference to this simulation. This cycle will be modified to be used with hydrogen as fuel.

This combined cycle-plant is composed by a single gas turbine, with triple pressure level, a reheat heat recovery, a steam generator and one steam turbine. Some assumptions have been adopted to allow the use of hydrogen like the reduction of the temperature at the entrance of the turbine until its nominal working value and the change into the compressor vanes to readjust the mass flow (discussed in the first chapter of this research). Hydrogen is supposed to be available at the required pressure.

In the case of premixed combustion, the process steps do not require any modification in comparation with the NG, the fuel is firstly preheated until 40ºC and then it goes to the gas turbine. On the other hand, for the diffusive flame with N_2, the hydrogen is also preheated at 40ºC and combined with the nitrogen which comes from a compressor, then the mix finds the air inside the combustion chamber. Finally, for the steam solution, the hydrogen is preheated at the same temperature and mixes with the steam, which comes at 300ºC, before the combustion chamber.

According to the results obtained from the first simulation, which uses a diffusive flame combustor with steam dilution,(Gazzani et al., 2014), we can observe that for all the cases, working at nominal temperature at the entrance of the turbine (with independence of the proportion of steam diluted), the gas turbine cycle provides a larger power compared to the original NG, thanks to the reduction into the compressor mass flow and its lower consume. In this case, the cycle produces 325,4 MW approximately 15% higher than the in the case of NG.

Otherwise, the steam power plant decreases its efficiency in a range of 27% to 7%. The total power production of the combined plant keeps as practically constant. Must be also highlighted that with those results we can observe a tendency of reduction in the efficiency of the combined plant with the increasing of the steam rate dilution in the hydrogen, at the same time as the steam dilution rises, the cooling flow rises too, as commented before, due to the change into heat transfer coefficient.

Looking at the cases with the same ratio of diluent but lower blade temperature, can be concluded that the reduction of the temperature at the entrance of the turbine reduces the turbine efficiency. To conclude, should be noted that the volumetric heating value of the hydrogen mixture varies in the range of 5800–9000 kJ/Nm^3, which is fairly equivalent to syngas typically burned in refinery plants.

Moving to the analysis of the second case, which uses a diffusive flame combustor and nitrogen as diluent, we can observe a significant increase into the power provided by the gas turbine, achieving 330 MW, nearly 17% more than the reference cycle. In this case, the diluent does not affect the power provided by the steam cycle. Otherwise, its power decreases a little bit compared to the reference due to the lower mass flow along the circuit, which reduces its value in 22 kg/s. This reduction is motivated firstly, because the volumetric flow rate is constant (about 166 m^3/s), as the first stator geometry is already determined (it has the rotor diameter and blade height).

Secondly, due to the specific volume of the working fluid increases. The increase in the flue gas–specific heat (due to the higher H_2O content) and the cooling flow rates do not balance the previous effects, motivating the decrease into the steam-power output (Gazzani et al., 2014).

In comparation with the previous case, the cooling flow required decreases in a range from 2% to 8% but compared to the original natural gas cycle it has a value of approximately 1.5% higher. The total plant efficiency reduces with the increase into the nitrogen dilution (as happened with steam). The gas plant efficiency decreases because the nitrogen requires the compressor before mixing with the hydrogen. The volumetric heating value for this dilution is between the range of 5000–8700 kJ/Nm^3, lower than in the case of the steam.

The last simulation from the research (Gazzani et al., 2014) corresponds to a premixed combustion, in this case we can observe a pressure drop of 3% working at the nominal temperature. At the same time can be seen that increasing the pressure drop in the combustion chamber provokes the reduction of the power of the cycle and its efficiency, due to the enthalpy drop motivated. Other factor involved is the reduction of the density of the gases at the entrance of the turbine, reducing its density provokes a decrease into the cooling flow required to protect the blades. Compared to the cycle of reference, we can observe an increase in the efficiency of the combined plant.

In Table 4 can be observed a summary of some of the most relevant results. In all cases, it is established a pressure ratio of 17, with the blades of the turbine working in their nominal temperature.

Type of combustion	Diffusive flame and steam	Diffusive flame and nitrogen	Premixed flame
Mass along the compressor (kg/s)	638	626,8	540,7
Hydrogen mass flow (kg/s)	6,14	6,06	5,83
Diluent/ hydrogen	2,6	5,55	-
Power gas cycle (MW)	301,2	303,1	275,4
Power steam cycle (MW)	126,5	137,6	135,6
Total Power (MW)	424	420,2	407,2
Combined cycle net efficiency (%)	57,56	57,78	58,19

Table 4 Summary of the main results obtained for each type of combustion**.**

A stochiometric flame temperature of 2500K for both cases of diffusive flame was determined and for the case of the premixed combustion a limited pressure loss of 6,5%, data obtained from the simulation (Gazzani et al., 2014). All data collected from the different simulations with different temperatures at the entrance of the turbine and different ratio of diluent (in the case of nitrogen and steam) can be consulted in table 5, 6 and 7 attached in the first appendix.

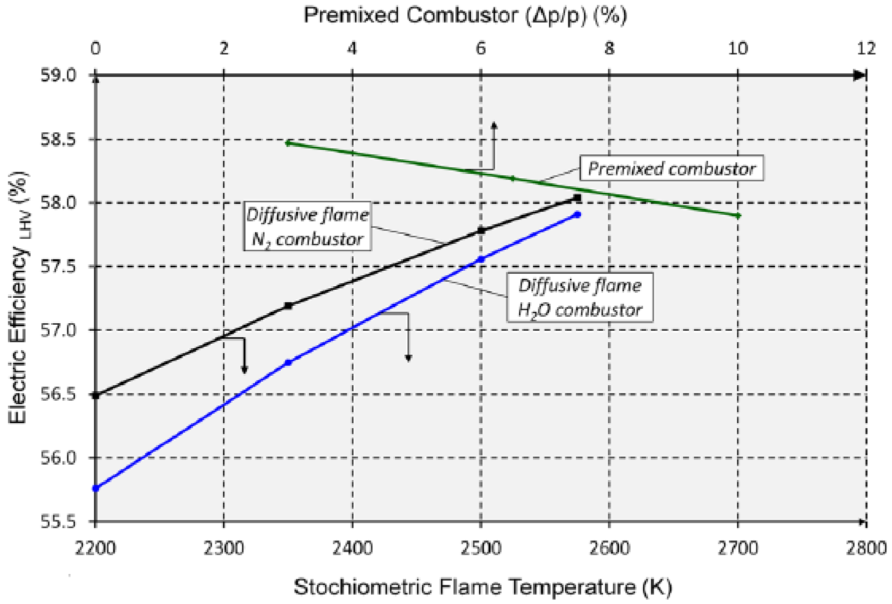


Figure 6 Combined cycle electric efficiency for all the cases at nominal TIT: the efficiency for steam- and nitrogen-diluted combustors is plotted as function of the STFT (bottom x-axis), while the efficiency for the premixed combustor is plotted as function of the combustor relative pressure loss (upper x-axis).(Gazzani et al., 2014).

After analysing the data obtained, can be extracted some general conclusions from this simulation, which are shown in Figure 6. In the chart, we can observe the efficiency of each kind of combustion system discussed in function of the stochiometric flame temperature, for the cases of diffusion flames and in function of the pressure drop in the case of the premixed system.

We can clearly observe that in the case of the diffusion flame, the efficiency provided when we use nitrogen as diluent is always higher than in the case of the steam. This difference is even larger when we are working with lower stochiometric flame temperatures (under 2400K), as can be seen comparing the slope of both lines. Otherwise, when we move to flame temperatures higher than 2400K, the efficiency of both diluent trend the same value, around 58%. On the other hand, can be concluded that the efficiency provided by the premixed combustor system is higher than diffusive flame, with even a larger difference when the pressure drop is lower.

3.4 Premixed lean direct injection combustion

In view that premixed combustion provides the best efficiency, it is time to deep in this system of combustion, showing their performances, efficiency and characteristics.

Due to the high reactivity of the hydrogen those kinds of burners should take into consideration the risk of flashback. Now will be discussed and assessed some burners and techniques that could be employed with hydrogen.

With the aim to eliminate the risk of flashback, we can find the lean direct injection (LDI), represented in Figure 7. LDI designs introduce fuel into excess air at the combustion zone from numerous (often hundreds or thousands) of locations as we can observe in Figure 7, through the blue canal, with the aim to achieve rapid mixing. NO_x emissions are typically marginally higher than a fully premixed system, flame anchoring on the injector may be an issue (York et al., 2013). Micromixers are composed by hundreds of those small ducts used as injectors as in the case of LDI but they also include a premixing zone before the combustion, this mix can be accomplished by several methods like jet-in-crossflow mixing, coflow mixing in channels and swirl-based mixing, among others.

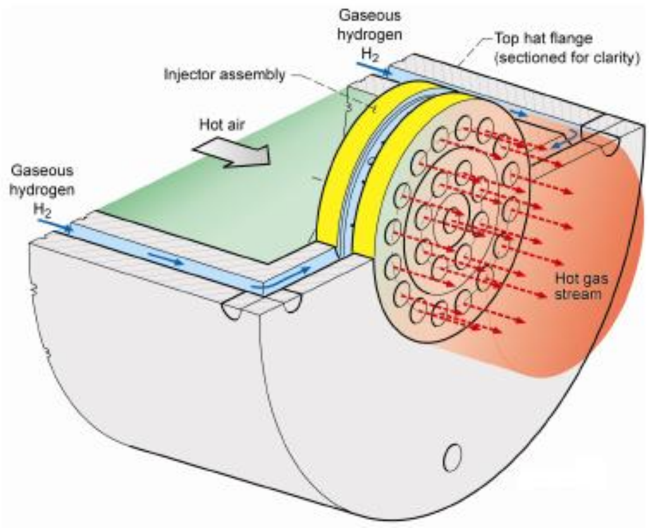


Figure7 Assembly of the configuration of a LDI burner (Marek et al., 2005).

Following these measures, the research (Marek et al., 2005) developed an simulation with the aim to assess the emissions and efficiency of different burners based on lean direct injection technology but with different configurations and also compare them when using Jet-A, a fuel used to supply gas turbines engines for planes. For every configuration with the aim to minimize the risks of flashback will be employed short mixing times and high velocities.

A total of five different injectors technology were tested in this simulation, one developed by NASA and the four reminders by some of the major fuel injector manufacturers with several years of experience in this industry. Initially, the air pressure drop was limited at 4%. However, some burners breached it, was also established an approximately air flow velocity at the entrance of the combustor of 30,5 m/s.

In the Figure 8 we can observe the different burners configuration tested in the research (Marek et al., 2005) starting with the upper left, we can observe the burner developed by NASA. This injector contains two opposing hydrogen jets in the mixing tube, the jet penetration and mixing system are based on jet in crossflow technology. According to (York et al., 2013), this premixing system uses the air flows through numerous straight tubes of millimetre-scale diameter in a parallel array between a front and back plate. The fuel injection takes place through many small holes distributed along the tube walls. To prevent flashbacks, the air speed in these tubes must be really high. This multitube mixer achieves a low pressure drop, not penalizing the efficiency of the combustion, as a result, it has very short area of premixing. This air ducts have a diameter of 0,635 cm while the hydrogen ducts will be smaller, being 0,508 cm.

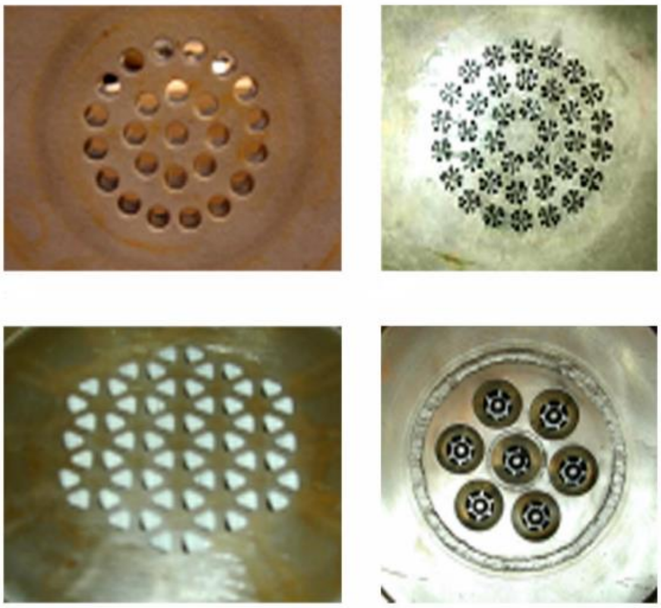


Figure 8 Pictures of four of the injectors tested (Marek et al., 2019).

Moving to the right, we can find the second burner tested, which will be called as configuration 1. It is based on previously rocket injection technology with a center “+” hydrogen jet and eight angled air jets mixing with the hydrogen. For this concept, a rich region was created near the face for ignition and flame holding using the four inner air jets of the air injection points. An immediate quench section was then created just downstream using the four-remaining air injection points. (Marek et al., 2005).

Continuum with the lower row, on the left part of the Figure 7, which will be designed as configuration 2, we can find a burner similar to the first one but in this case with triangular holes instead of circles. This configuration reduces the size of the elements but otherwise increases its number combined with some additional points to injects the hydrogen. These variations have the aim to motivate the mix of both components to stimulate the combustion. Specifically, it contains 54 triangular LDI injectors with 3 hydrogen injection points per triangle in a honeycomb pattern.

Finishing with the last image of Figure 7, configuration 3 is a conservative design based on the already existing technology used in gas turbine. It is composed by a single center hydrogen nozzle at the center of each hole with a large amount of counter swirl to produce mixing. This design includes a single hole hydrogen injection with counter swirl for each of the seven LDI holes.

The last configuration (configuration 4) tested is based on configuration three (left lower row of Figure 7). However, the center hole is replaced by four small radial diameter hydrogen jets per injection point, in this configuration does not exist air swirl with the aim to reduce pressure drop. (Marek et al., 2005).

As can be observed in Figures 12 to 15 of the first appendix, where are recorded the data obtained for each configuration comparing the use of hydrogen and Jet-A as fuels, must be highlighted some issues. In configuration two, the NO_x levels were very low, achieving less than half of the Jet-A levels, but its cooling and durability was compromised. It failed resulting in nonuniform mixing and higher NO_x (Marek et al., 2005).

In the case of the third configuration, the NO_X emissions were half than in the case of using Jet-A as fuel. The last configuration also proofed to be very durable and able to be tested along a wide range of temperatures, showing an emission of NO_x much lower than when Jet-A is employed.

Figure 9 shows the emissions provided by each kind of configuration, in every configuration based on lean direct injection is not observed high levels of NO_x emissions. As was predicted did not take place any phenomenon of flashback or autoignition.

According to the data obtained, the configuration number four would be the best option from the criteria of low emission and durability. As a general phenomenon observed in this test (Marek et al., 2005) when there are the more points of injection, the lower NO_x emissions are produced. Must be also mentioned that every injector exposed requires big effort in term of design and manufacturing what implies an increase in its costs.

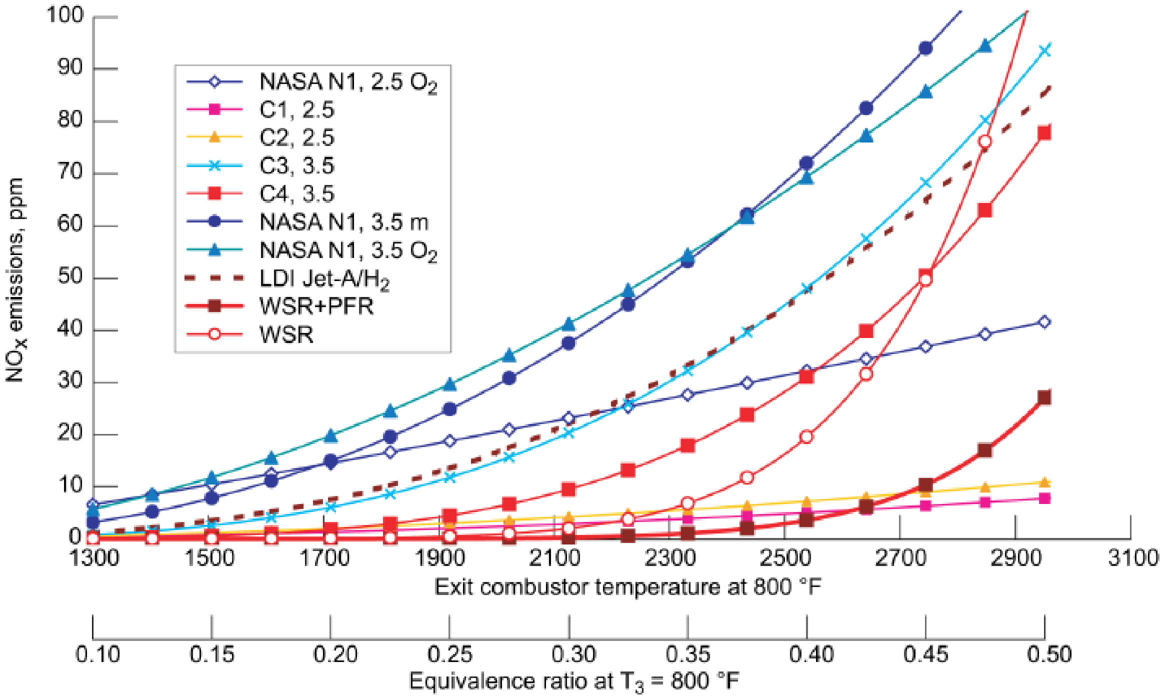


Figure 9 NO_x emissions for all configurations, with a temperature at the entrance of 427 ºC (800ºF) and a pressure drop of 4% (Marek et al., 2005).

4.- Where could hydrogen be obtained from?

4.1 Classification of hydrogen

Once studied and discussed the effects and the changes which must be accomplished to used hydrogen as fuel in heavy duty gas turbine and the different system which can be used. This final part of the research will be mainly dedicated to expose and discuss some of the methods we can use to get hydrogen to supply these turbines, trying to show the benefits or disadvantages of each.

Before going through these methods, hydrogen can be classified depending on the source it comes from and the technique employed, this classification is based on colours. Firstly, we have the green hydrogen, it refers to the hydrogen produced using renewable energy. It involves many systems like using wind, solar or biomass energy to produce electricity and generate the electrolysis of the water, dividing the molecules of H_2O in, on the one hand H_2 and on the other O_2. This is the most sustainable and friendliest with the environment way of producing hydrogen because it does not produce any kind of greenhouse emissions to the atmosphere. Unfortunately, it just involves 1% of the global production (Nogales, 2021).

In second place we can find the blue hydrogen, it involves the hydrogen obtained from fossil sources, generally from natural gas or petroleum, this process also involves the emission of CO_2. In the case of blue hydrogen, this greenhouse gases are captured so they do not reach the atmosphere. This system is not as friendly with the environment as the first one but it does not involve a significant damage to the atmosphere.

Continuing with the classification and really similar to the previous one, we can find the gray hydrogen. It is hydrogen produced from the same sources as blue hydrogen but in this case the greenhouse gases produced are not captured, they are discharged into the atmosphere. This is the cheapest way of producing hydrogen and nowadays corresponds to the 70% global production (Nogales, 2021). We can also find other colors like brown, it is the same as grey but using coal instead of natural gas. Should also be mentioned the white hydrogen, it refers to the hydrogen stored in the nature, in underground deposits. Probably one day they could be extracted but currently we do not have this technology available. Other lesser-known variants would be pink hydrogen, obtained through nuclear energy using the electrolysis process, something that is also quite sustainable (Nogales, 2021).

As can be seen in Figure 10, in 2009 approximately 96% of the global production of hydrogen employed fossil resources, generation the emission of greenhouse gases, mostly of those from the reforming of methane (system discussed in the next subchapter).

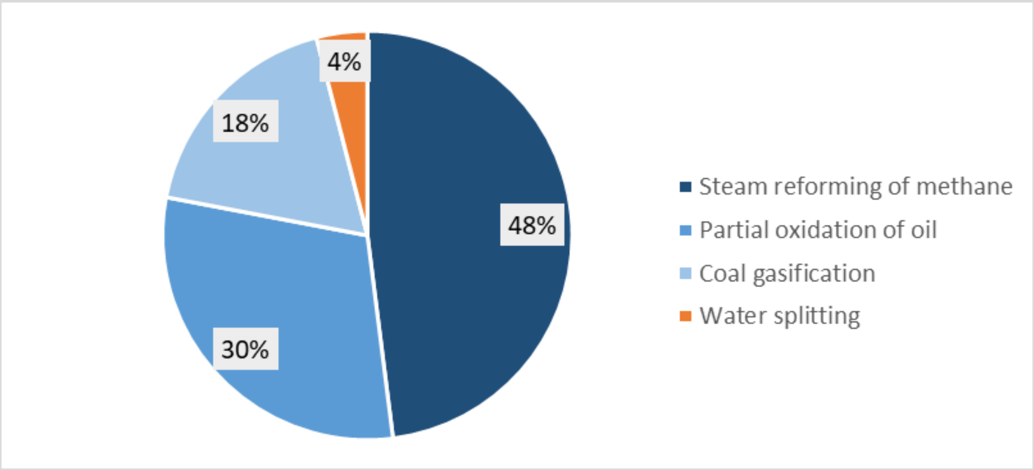


Figure 10 Hydrogen production processes (blue shares correspond to those methods that use fossil fuels **(Balat & Balat, 2009)**.

4.2 Methods to produce hydrogen

Following with this research will be briefly explained three ways of producing hydrogen, the first one through the electrolysis of water, then by steam reforming of natural gas and finally by the gasification of coal.

The first method exposed will be the electrolysis of water, it is mainly used when the amount of hydrogen required is not much large. Nowadays, it is the best-known system to produce hydrogen, it is based on the separation of the atoms of water using electricity.

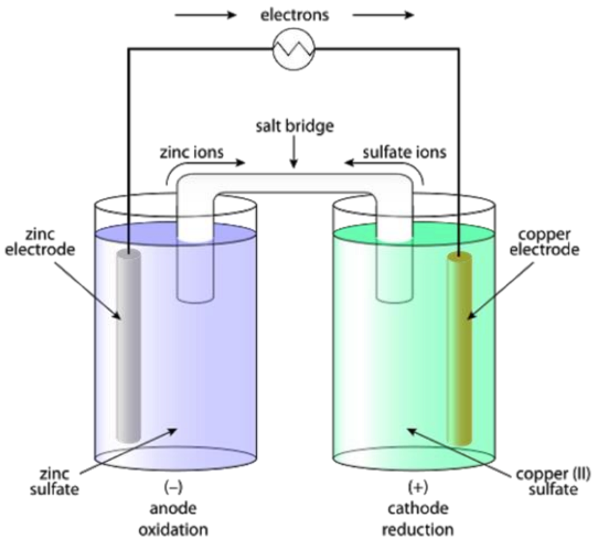


Figure 11 Outline of an electrolitic cell (Angelovska, 2016)

The electrodes, cathode and anode, are situated in the solution and generate the movement of electrons. The hydrogen is formed in the cathode, at the same time but in half of the volume of the hydrogen, due to the composition of the molecule of water, the oxygen does it in the anode. With the aim to improve the production of both elements it is usually changed the composition of the water, by the addition of salts, to improve the speed of the reaction, according to the research (Fernandez, 2005), the efficiency of this system is around 75%.

This hydrogen produced must be purify because it contains oxygen impurities and a certain level of humidity. The costs of production by this method are around 4,9-5,6 KWh per m^3 of hydrogen produced, resulting two times more expensive than reforming natural gas. (G.Fierro, 2011). With the intention to reduce these costs, we can also find the electrolysis but in vapor phase. In this case the costs of production are proportional to the electricity used and it decreases with the temperature, at 1.500K the costs required to produce H_2 are approximately 50% lower (G.Fierro, 2011).

As has been shown, the requirement for this system is the use of electricity to divide the molecules of water. Thus, depending on the source, we are getting this electricity from we could be talking of a completely sustainable production, with no pollution of the environment or otherwise, of a production system not such respectful with the environment.

The second technique to the production of hydrogen is based on the steam reforming of natural gas, specially of the methane it contains. This method relates the two components discussed along this research, below is shown the stochiometric reaction which takes place:

$$CH_4 + H_2O \longrightarrow CO + 3H_2 \qquad (3)$$

As can be seen, the NG reacts with the steam to produce carbon monoxide and hydrogen. This reaction develops at high temperature and pressure, previously the NG requires a process of purification to remove sulfur impurities it may contain. Then the stream of clean methane reacts in a reactor with the presence of nickel, used as catalysator, to increase the speed of the reaction. The exhausted gases are rich in hydrogen but with a large amount of carbon monoxide. These gases react in another reactor with the presence of steam to produce more hydrogen. The resulting gas has a high proportion of hydrogen, with CO_2 and lower quantity of non-transformed methane and carbon monoxide in around 1% of the volume (G.Fierro, 2011).

The modern plants also incorporate units to purify the gases, obtaining a 99,999% pure hydrogen in volume (G.Fierro, 2011). According to (Fernandez, 2005), the efficiency of this system is around 70%, a little lower than in the case of electrolysis.

This process is widely used in the industry because is the cheapest, according to the “Office of Energy efficiency & renewable energy”, the 95% of the hydrogen produced in the United Stated is produced with this system.

Instead of methane could also be used methanol which reacts with steam to produce hydrogen. This is an endothermic reaction which uses the heat coming from burning some part of the methanol. As in the case of the methane, the exhausted gases must also be purified. On the other hand, this reaction is simpler because does not take into account the formation of intermediate oxygenates (G.Fierro, 2011), but due to its higher cost it is less used.

The third and last system which will be discussed consist into gasification of coal, it consists in the production of hydrogen from coal. It starts by heating the solid coal until it becomes a gas, then this gas reacts with steam and oxygen to produce hydrogen, carbon monoxide and carbon dioxide.

Deepening a little into the reaction, this process requires two reactions, in the first one we obtain carbon monoxide from the coal and the second one transforms this monoxide in carbon dioxide, both give off hydrogen, each one takes place in a different reactor because they requiere different temperatures.

This system is nearly two times more expensive than obtaining hydrogen from NG, due to the ratio of hydrogen-carbon in the NG is 4:1 while in coal is 0,8:1 (Fernandez, 2005), and must also be highlighted that the emissions of carbon dioxide it produces are larger than in case of the NG so they should be captured.

Once exposed these different systems of producing hydrogen, must be said that one of the most important reason of moving from fossil fuels to hydrogen is because of the reduction of the environmental impact. This change would not be so useful if the production of this hydrogen keeps polluting the atmosphere. This is an issue which requires more investigation and development with the aim to create new and affordable systems or methods which employ renewable sources to carry out this task.

5.- Conclusion

Currently, a world without electricity would be unthinkable. One part of this electricity is produced using heavy duty gas turbines. With the aim to respect the environment, they could be transformed into low or zero-carbon emitting systems. This task can be done through pre- or post-combustion options. Pre-combustion choices include the use of hydrogen or any other renewable source. Post-combustions options include carbon capture and oxyfuels (Goldmeer, 2020). This investigation opts for the first solution.

During this research, the implications and the requirements of changing from a NG gas turbine to one fueled with hydrogen have been shown and some conclusions were discussed. Regarding the process of combustion, we can find two different systems: diffusive and premixed flame. The first one is widely used in this kind of turbines, while the second one is under development.

Due to properties of hydrogen, specially its higher stochiometric flame temperature compared to NG, when using a diffusive combustion system, a diluent should be included, otherwise the production of NO$_x$ would be excessive. We can find two diluents: nitrogen and steam. According to the different experiments and research reviewed, it can be concluded that nitrogen provides the best performances, generating the lower efficiency drop.

To accommodate this new diluent and its impact on the turbomachinery, different methods have been discussed. Overall, adjusting the variable guide vanes of the compressor appears to be a better solution than changing the pressure ratio. However, the best solution would consist in the design and construction of a new cycle, but this is not the aim of this research.

Moving to the premixed system, it has proved to be the one with higher efficiency in different tests. However, this system still requires development and research even though many advances have been made. This system has to mainly take care of the risk of flashback. With the aim to minimize them, the lean direct injection has been explained in this research. They are a system of combustors which operate in a fuel lean mode and achieve rapid mixing of fuel and air using hundreds or thousands of small-scale mixers. They provide a good efficiency with a low production of NO$_x$, although unfortunately, they require a hard and difficult process of design, manufacture and production, circumstances which increase its price.

However, one of the most limiting factors regarding hydrogen is its production. Nowadays, established, large-scale, renewable-based hydrogen production does not exist. In this research, three different systems have been explained, but it is mandatory to find a non-pollutant system of production which allows to produce hydrogen in large scale to supply these turbines.

As a general conclusion, it can be said that pre-existing gas turbine cycles can be run with hydrogen. This will imply a huge step to achieve the reduction of greenhouse gases trying to reverse the current climate change that we are facing and moving towards a more sustainable world.

Figures and tables

Tables

Figures

Figures and tables

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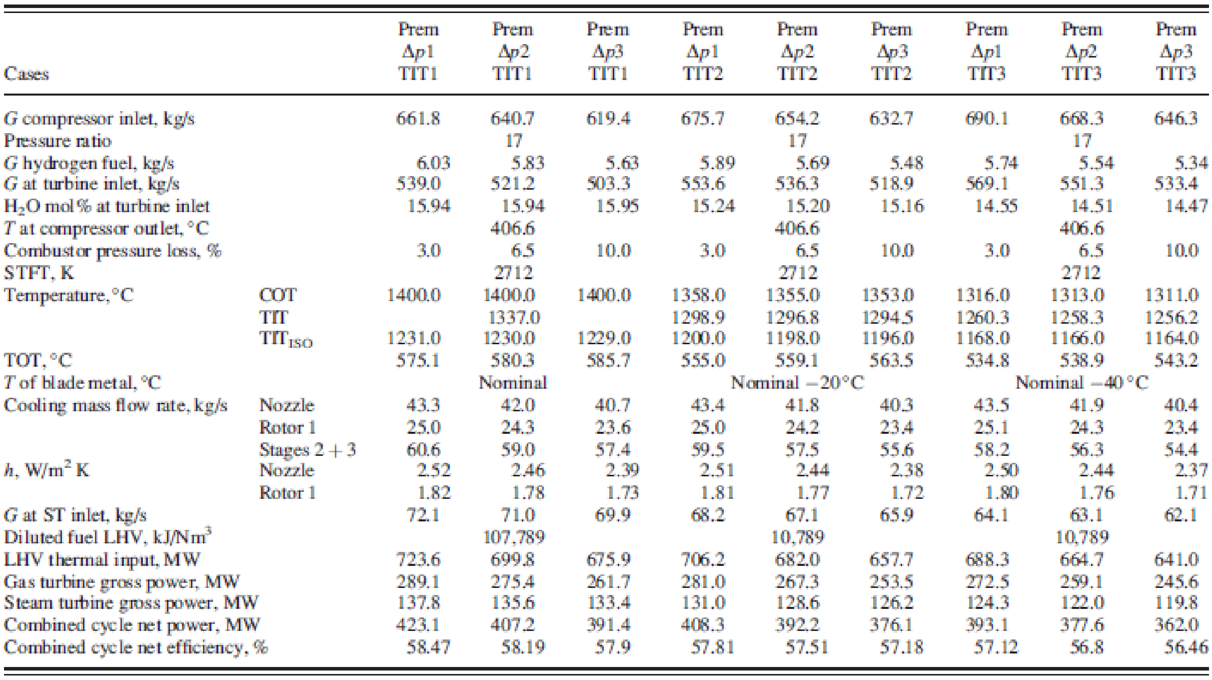
Appendix

Cases		H_2O NO_x1 TIT1	H_2O NO_x2 TIT1	H_2O NO_x3 TIT1	H_2O NO_x4 TIT1	H_2O NO_x1 TIT2	H_2O NO_x2 TIT2	H_2O NO_x3 TIT2	H_2O NO_x4 TIT2	H_2O NO_x1 TIT3	H_2O NO_x2 TIT3	H_2O NO_x3 TIT3	H_2O NO_x4 TIT3
G compressor inlet, kg/s		647.1	638.0	616.8	590.7	661.4	652.4	631.7	607.0	676.2	667.4	647.1	623.1
Pressure ratio		17				17				17			
G hydrogen fuel, kg/s		6.10	6.14	6.24	6.37	5.95	5.99	6.09	6.17	5.80	5.84	5.93	6.00
G diluent/*G* hydrogen		1.62	2.60	4.86	7.56	1.61	2.60	4.85	7.56	1.61	2.60	4.85	7.56
G at turbine inlet, kg/s		531.9	527.6	517.4	504.8	546.8	542.4	532.4	524.8	562.4	557.9	548.1	540.6
H_2O mol% at turbine inlet		18.84	20.65	24.88	30.17	18.00	19.73	23.76	28.40	17.17	18.82	22.64	27.06
T at compressor outlet, °C		406.7				406.6				406.6			
STFT, K		2575	2500	2350	2200	2575	2500	2350	2200	2575	2500	2350	2200
Temperature, °C	COT	1400.0	1400.0	1401.0	1401.9	1358.0	1359.0	1360.0	1349.9	1316.0	1317.0	1319.0	1308.9
	TIT	1337.0				1298.9	1299.4	1299.7	1290.9	1260.6	1261.2	1261.9	1254.0
	TIT_{ISO}	1230	1230	1228	1225.9	1199.0	1199.0	1198.0	1190.9	1168.0	1168.0	1167.0	1160.9
NO_x, ppmvd 15% O_2		250.3	159.3	58.9	19.0	241.3	153.3	56.6	18.0	232.2	147.4	54.3	17.1
TOT, °C		578.2	580.0	584.4	589.7	557.8	559.6	563.7	564.8	537.5	539.2	543.1	544.1
T of blade metal		Nominal				Nominal −20°C				Nominal −40°C			
Cooling mass flow rate, kg/s	Nozzle	44.0	44.4	45.5	46.9	44.1	44.5	45.6	45.6	44.1	44.6	45.6	45.7
	Rotor 1	25.4	25.7	26.3	27.2	25.4	25.7	26.4	26.4	25.5	25.8	26.5	26.5
	Stages 2 + 3	61.7	62.4	64.1	66.3	60.6	61.3	63.0	63.0	59.3	60.1	61.7	61.7
h, W/m^2 K	Nozzle	2.55	2.57	2.63	2.69	2.54	2.56	2.61	2.66	2.53	2.55	2.59	2.64
	Rotor 1	1.84	1.86	1.89	1.94	1.83	1.84	1.88	1.92	1.82	1.83	1.86	1.90
G at ST inlet, kg/s		73.3	74.1	75.9	78.3	69.4	70.2	71.9	73.1	65.2	65.9	67.6	68.6
Diluted fuel LHV, kJ/Nm^3		9054.7	8270.9	6916.0	5786.6	9057.4	8269.5	6916.3	5786.6	9056.8	8269.9	6916.7	5786.4
LHV thermal input, MW		731.6	736.7	748.7	763.9	713.9	719.0	730.4	739.7	695.7	700.5	711.4	720.2
Gas turbine gross power, MW		296.5	301.2	312.0	325.4	288.3	293.0	303.6	314.9	279.7	284.2	294.6	305.7
Steam turbine gross power, MW		130.9	126.5	116.4	103.8	124.1	119.9	110.0	96.1	117.5	113.4	103.5	90.0
Combined cycle net power MW		423.6	424.0	424.9	425.9	408.8	409.3	410.2	407.9	393.7	394.2	394.9	392.6
Combined cycle net efficiency, %		57.91	57.56	56.75	55.76	57.27	56.93	56.15	55.13	56.59	56.27	55.51	54.51

Table 5 Results for the hydrogen-fueled combined cycle with diffusive flame combustor and steam dilution. Nomenclature: H2O: steam dilution; NOx1-2-3-4: ordered with decreasing STFT (2575, 2500, 2350, 2200 K); TIT1-2-3: ordered with decreasing TIT (or blade metal temperature), 1 is the nominal temperature, 2 and 3 correspond to a metal temperature decrease of 20ºC or 40ºC, respectively (Gazzani et al., 2014).

Cases		N_2 NO_x1 TIT1	N_2 NO_x2 TIT1	N_2 NO_x3 TIT1	N_2 NO_x4 TIT1	N_2 NO_x1 TIT2	N_2 NO_x2 TIT2	N_2 NO_x3 TIT2	N_2 NO_x4 TIT2	N_2 NO_x1 TIT3	N_2 NO_x2 TIT3	N_2 NO_x3 TIT3	N_2 NO_x4 TIT3
G compressor inlet, kg/s		640.0	626.8	596.7	560.5	654.5	641.5	612.1	576.8	669.5	656.9	628.2	593.7
Pressure ratio		17				17				17			
G hydrogen fuel, kg/s		6.05	6.06	6.09	6.13	5.91	5.92	5.95	5.98	5.76	5.77	5.80	5.83
G diluent/*G* hydrogen		3.46	5.55	10.30	15.93	3.45	5.55	10.29	15.93	3.45	5.55	10.29	15.93
G at turbine inlet, kg/s		538.3	537.9	537.1	536.0	553.0	552.6	551.7	550.7	568.4	568.1	567.2	566.2
H_2O mol% at turbine inlet		15.95	15.95	15.96	15.98	15.25	15.26	15.27	15.28	14.56	14.56	14.58	14.59
T at compressor outlet, °C		406.6				406.6				406.6			
STFT, K		2575	2500	2350	2200	2575	2500	2350	2200	2575	2500	2350	2200
Temperature, °C	COT	1400.0	1400.0	1400.0	1400.0	1358.0	1358.0	1358.0	1358.0	1316.0	1316.0	1316.0	1315.9
	TIT	1337.0				1298.9	1299.0	1299.0	1298.9	1260.0	1260.0	1260.0	1260.4
	TIT_{ISO}	1231.0	1231.0	1231.0		1200.0	1200.0	1200.0	1200.0	1168.0	1168.0	1168.0	1167.9
NO_x, ppmvd 15% O_2		250.4	159.5	58.9	19.0	241.6	153.4	56.6	18.1	232.6	147.5	54.2	17.3
TOT, °C		575.0	574.9	574.7	574.4	554.8	554.7	554.5	554.2	534.7	534.6	534.4	534.2
T of blade metal, °C		Nominal				Nominal −20°C				Nominal −40°C			
Cooling mass flow rate, kg/s	Nozzle	43.3	43.3	43.3	43.3	43.4	43.4	43.4	43.4	43.5	43.5	43.5	43.5
	Rotor 1	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.0	25.1	25.1	25.1	25.1
	Stages 2 + 3	60.5	60.4	60.2	59.9	59.4	59.3	59.1	58.8	58.1	58.0	57.8	57.6
h, W/m^2 K	Nozzle	2.51	2.51	2.51	2.51	2.50	2.50	2.50	2.50	2.49	2.49	2.49	2.49
	Rotor 1	1.82	1.82	1.82	1.82	1.81	1.81	1.81	1.81	1.80	1.80	1.80	1.80
G at ST inlet, kg/s		72.0	72.0	71.9	71.8	68.2	68.1	68.0	67.9	64.0	64.0	63.9	63.8
Diluted fuel LHV, kJ/Nm^3		8639.9	7709.0	6197.3	5025.9	8642.2	7709.3	6198.0	5026.7	8642.8	7710.2	6198.2	5026.8
LHV thermal input, MW		725.8	727.3	730.8	734.8	708.6	710.0	713.3	717.2	690.6	692.0	695.2	699.1
Gas turbine gross power, MW		297.8	303.1	315.3	329.9	289.6	294.8	306.6	320.9	280.9	285.9	297.5	311.4
Steam turbine gross power, MW		137.7	137.6	137.5	137.3	130.9	130.8	130.7	130.5	124.1	124.1	123.9	123.8
Nitrogen compressor power, MW		−10.3	−16.6	−31.0	−48.2	−10.1	−16.2	−30.2	−47.1	−9.8	−15.8	−29.5	−45.9
Combined cycle net power, MW		421.3	420.2	417.9	415.1	406.6	405.6	403.3	400.5	391.5	390.6	388.3	385.6
Combined cycle net efficiency, %		58.04	57.78	57.19	56.49	57.38	57.12	56.54	55.84	56.69	56.44	55.86	55.16

Table 6 Results for the hydrogen-fueled combined cycle with diffusive flame combustor and nitrogen dilution. Nomenclature: N2: nitrogen dilution; NOx1-2-3-4: ordered with decreasing STFT (2575, 2500, 2350, 2200 K); TIT1-2-3: ordered with decreasing TIT (or metal blade temperature), 1 is the nominal temperature, 2 and 3 correspond to a decrease of 20ºC or 40ºC on the metal, respectively (Gazzani et al., 2014).



Cases		Prem $\Delta p1$ TIT1	Prem $\Delta p2$ TIT1	Prem $\Delta p3$ TIT1	Prem $\Delta p1$ TIT2	Prem $\Delta p2$ TIT2	Prem $\Delta p3$ TIT2	Prem $\Delta p1$ TIT3	Prem $\Delta p2$ TIT3	Prem $\Delta p3$ TIT3
G compressor inlet, kg/s		661.8	640.7	619.4	675.7	654.2	632.7	690.1	668.3	646.3
Pressure ratio			17			17			17	
G hydrogen fuel, kg/s		6.03	5.83	5.63	5.89	5.69	5.48	5.74	5.54	5.34
G at turbine inlet, kg/s		539.0	521.2	503.3	553.6	536.3	518.9	569.1	551.3	533.4
H_2O mol% at turbine inlet		15.94	15.94	15.95	15.24	15.20	15.16	14.55	14.51	14.47
T at compressor outlet, °C			406.6			406.6			406.6	
Combustor pressure loss, %		3.0	6.5	10.0	3.0	6.5	10.0	3.0	6.5	10.0
STFT, K			2712			2712			2712	
Temperature, °C	COT	1400.0	1400.0	1400.0	1358.0	1355.0	1353.0	1316.0	1313.0	1311.0
	TIT		1337.0		1298.9	1296.8	1294.5	1260.3	1258.3	1256.2
	TIT_{ISO}	1231.0	1230.0	1229.0	1200.0	1198.0	1196.0	1168.0	1166.0	1164.0
TOT, °C		575.1	580.3	585.7	555.0	559.1	563.5	534.8	538.9	543.2
T of blade metal, °C			Nominal			Nominal −20°C			Nominal −40 °C	
Cooling mass flow rate, kg/s	Nozzle	43.3	42.0	40.7	43.4	41.8	40.3	43.5	41.9	40.4
	Rotor 1	25.0	24.3	23.6	25.0	24.2	23.4	25.1	24.3	23.4
	Stages 2 + 3	60.6	59.0	57.4	59.5	57.5	55.6	58.2	56.3	54.4
h, W/m^2 K	Nozzle	2.52	2.46	2.39	2.51	2.44	2.38	2.50	2.44	2.37
	Rotor 1	1.82	1.78	1.73	1.81	1.77	1.72	1.80	1.76	1.71
G at ST inlet, kg/s		72.1	71.0	69.9	68.2	67.1	65.9	64.1	63.1	62.1
Diluted fuel LHV, kJ/Nm^3			107,789			10,789			10,789	
LHV thermal input, MW		723.6	699.8	675.9	706.2	682.0	657.7	688.3	664.7	641.0
Gas turbine gross power, MW		289.1	275.4	261.7	281.0	267.3	253.5	272.5	259.1	245.6
Steam turbine gross power, MW		137.8	135.6	133.4	131.0	128.6	126.2	124.3	122.0	119.8
Combined cycle net power, MW		423.1	407.2	391.4	408.3	392.2	376.1	393.1	377.6	362.0
Combined cycle net efficiency, %		58.47	58.19	57.9	57.81	57.51	57.18	57.12	56.8	56.46

Table 7 Results for the hydrogen-fueled combined cycle with premixed combustor. Nomenclature: prem: premixed combustor; Dp 1-2-3: ordered with increasing combustor pressure loss (3.0%, 6.5%, 10.0%); TIT1-2-3: ordered with decreasing TIT (or metal blade temperature), 1 is the nominal temperature, 2 and 3 correspond to a decrease of 20ºC or 40ºC on the metal, respectively (Gazzani et al., 2014).

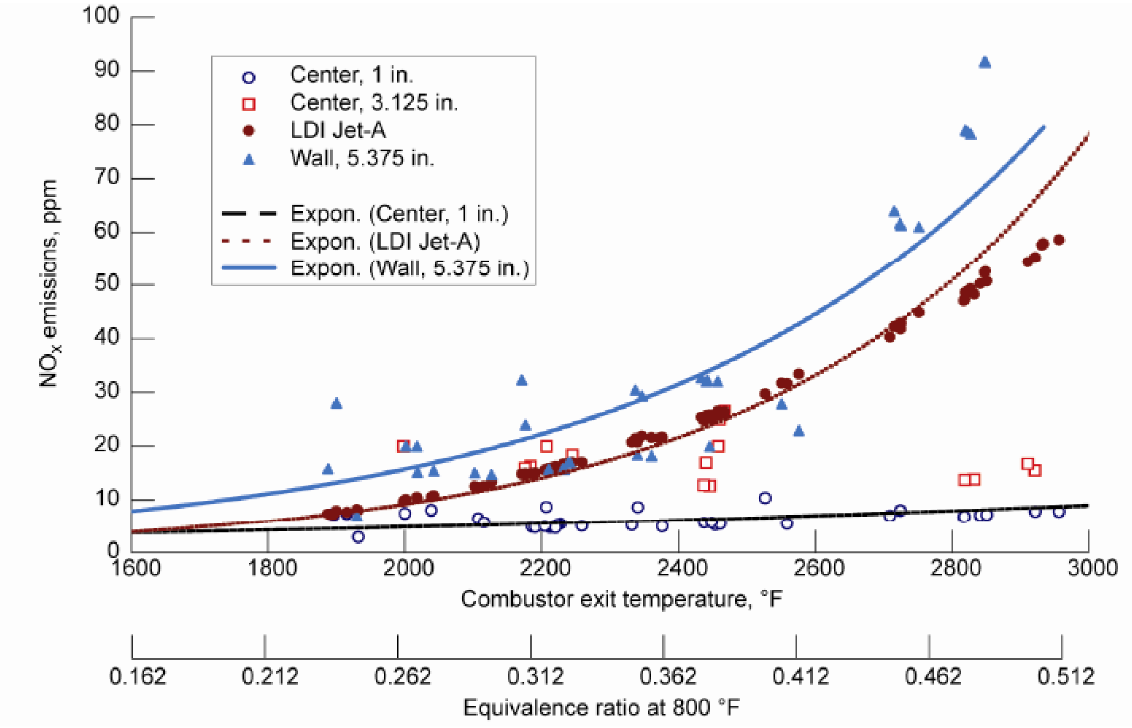


Figure 12 Emissions of the injector designed by NASA, with 63,5 mm of liner, an inlet temperature of 427ºC and an air flow speed of 40 m/s(Marek et al., 2005).

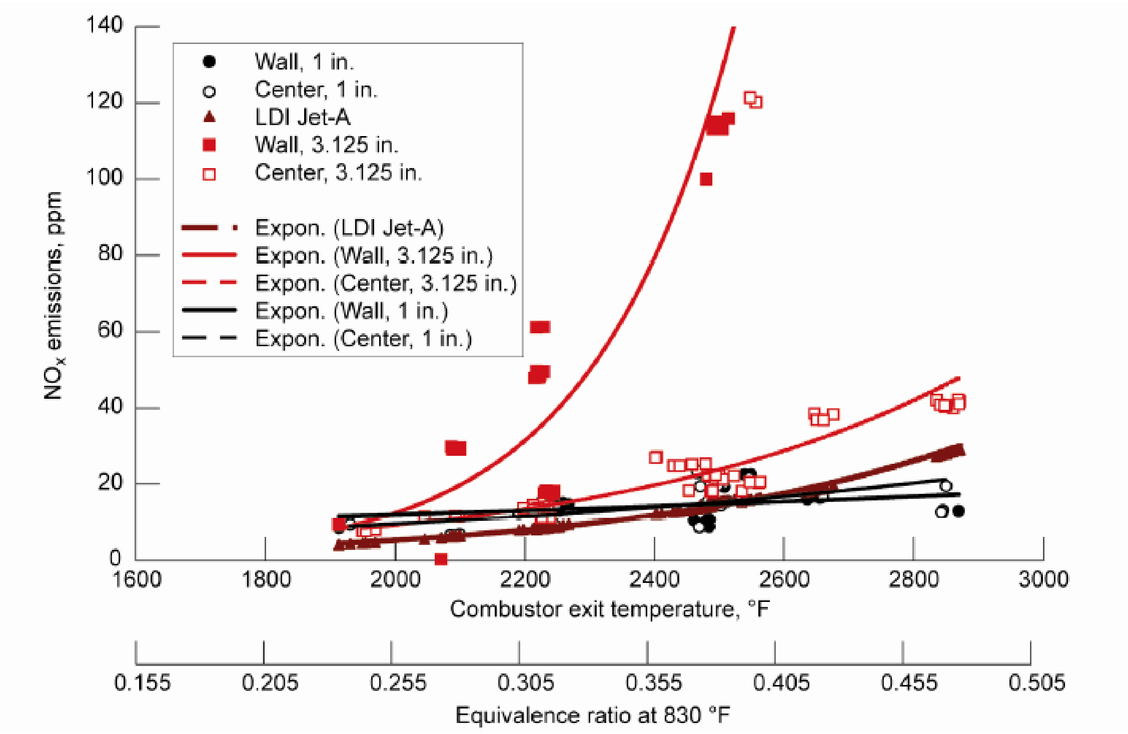


Figure 13 Emissions of the injector in configuration 1, with 63,5 mm of liner, an inlet temperature of 443ºC and an air flow speed of 30,5 m/s (Marek et al., 2019).

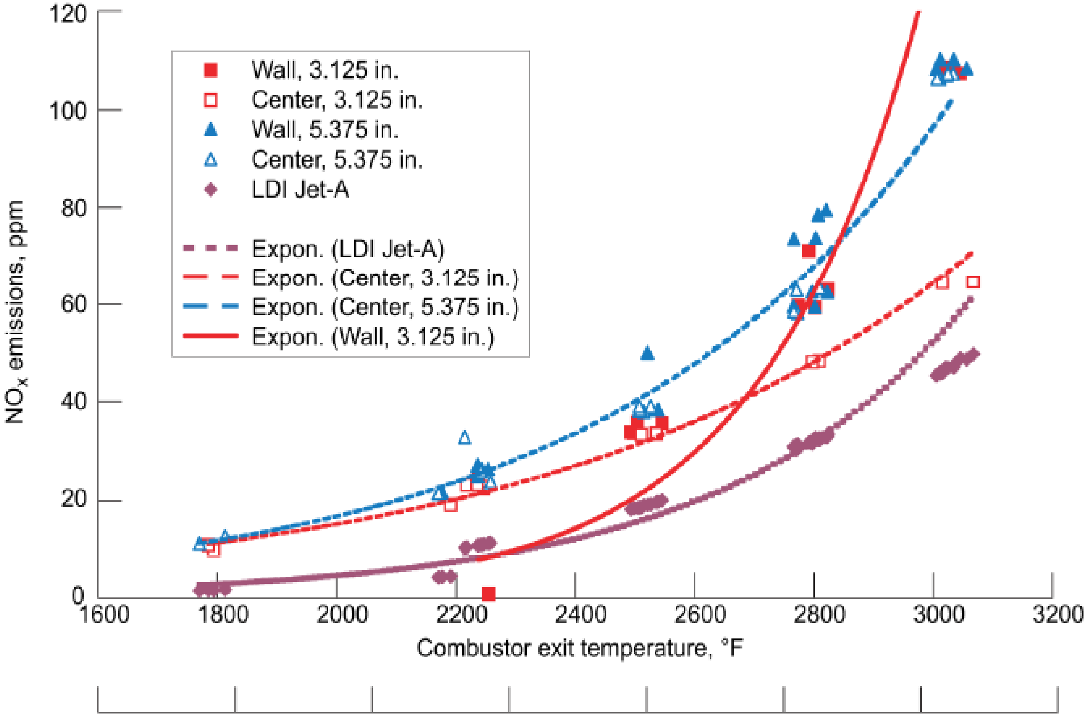


Figure 14 Emissions of the injector in configuration 3, with 63,5 mm of liner, an inlet temperature of 427ºC and an air flow speed of 21 m/s (Marek et al., 2019).

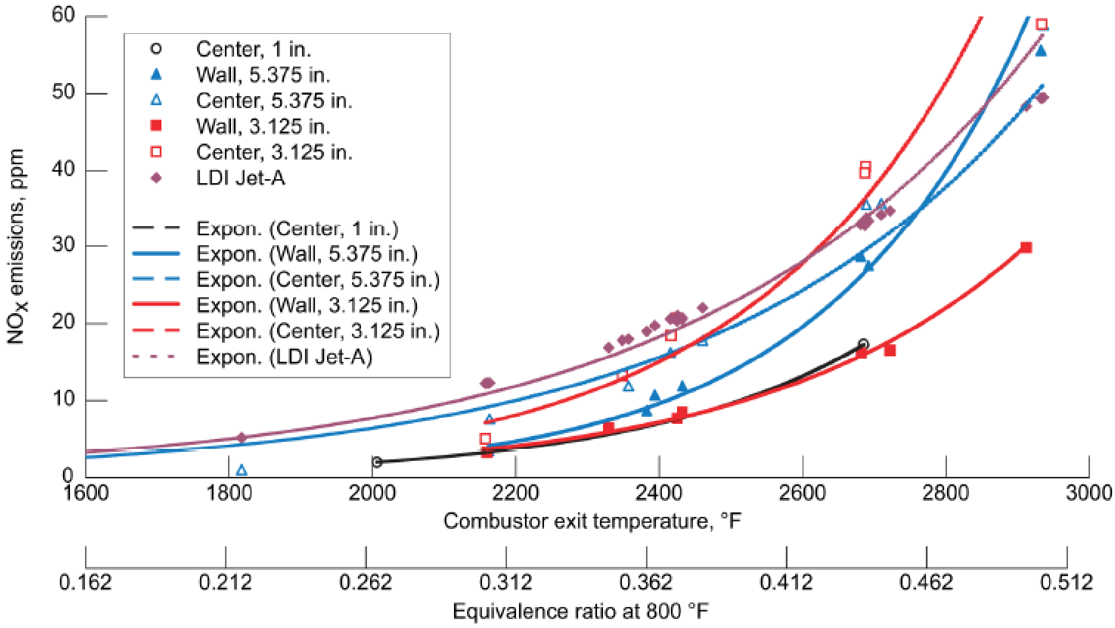


Figure 15 Emissions of the injector in configuration 4, with 88,9 mm of liner, an inlet temperature of 427ºC and an air flow speed of 18 m/s (Marek et al., 2019).