High Hydrogen Fuels in Fired Heaters

Charles Baukal[1], Bill Johnson[1], Michel Haag[2], Gilles Theis[2],
Mike Henneke,[1] Vance Varner,[1] Kirk Wendel,[1]

John Zink Hamworthy Combustion
Tulsa, OK, U.S.A.[1] and Dudelange, Luxembourg[2]

Abstract

Hydrogen is a distinctive fuel in many ways. For example, it has the potential to eliminate both carbon monoxide and carbon dioxide emissions. However, it could increase NOx emissions compared to more conventional fuels. Hydrogen has many unique properties such as a wider flammability range, higher adiabatic flame temperature, higher flame speed, lower heating value on a volume basis, and lower combustion air requirements compared to many common fuels. Some potential safety concerns include a higher propensity to flash back on pre-mix burners because of the higher flame speed and to leak because H_2 is a very small and volatile molecule. Because of its many unique properties, there are some important design considerations when retrofitting a combustion system designed to use a conventional fuel like natural gas to use hydrogen. This paper investigates some of the key differences when using hydrogen as a fuel compared to typical hydrocarbons. It considers the impact on: the fuel and air delivery systems, flame detection, burner design, heat transfer, pollution emissions, and safety. It includes some specific implementation examples in fired heaters.

1. Introduction

Interest in hydrogen as a fuel continues to grow, in large part because it generates water when combusted, with little if any carbon dioxide generated, depending on how the hydrogen is produced. The U.S. Department of Energy has developed a concept called H2@Scale to explore the potential for wide-spread hydrogen production and utilization in the United States [1]. A National Energy Renewable Laboratory report provides projections for the technical and economic potential of hydrogen production from a wide range of sources if the H2@Scale project is successful [2].

In the past, using hydrogen as a fuel was only economical in certain applications. Reducing CO_2 emissions and concerns about fossil fuel depletion are two of the major drivers for more applications considering the use of high hydrogen fuels [3].

Hydrogen has the potential to be an important green fuel depending on how the hydrogen is generated [4]. Hoffman notes that hydrogen is an energy carrier, rather than an energy source, because unlike fuels such as oil and natural gas, hydrogen does not exist in nature as H_2 [5]. Today, hydrogen is commonly produced on a large scale in hydrogen reformers. Natural gas and naphtha are the most common feed materials for this process [6]. Steam-methane reforming (SMR) is currently the preferred method for large scale production of hydrogen because of the low cost of natural gas, lower energy demands compared to other methods, and a relatively low quantity of heavy residuals [7]. It accounts for about 95% of the hydrogen produced in the U.S. [8]. These SMR processes react steam and methane in catalyst-filled tubes located inside a furnace heated by the combustion of fossil fuels. The hydrogen concentration is further increased by pressure swing adsorption. Those SMR furnaces generate CO_2 emissions. If those CO_2 emissions are captured, this is referred to as "blue hydrogen" [9]. If the CO_2 is not captured, this is referred to as "grey hydrogen." If hydrogen is produced, for example, by electrolysis and the electricity is produced by burning coal, this is referred to as "brown hydrogen" [10]. However, if hydrogen is made with renewable energy, such as wind or solar energy powering an electrolysis process, then CO_2 would not be generated during hydrogen production. This is referred to as "green hydrogen."

There continues to be an increased demand for hydrogen in many petrochemical plants, for example, for increased hydrotreating and hydrocracking processes such as processing sour crudes [11, 12]. Two strong drivers for the increased demand include environmental regulations and feedstock shortages [13]. Other drivers include: increased diesel and middle distillates proportions, strategic mixes of heavier and sour crudes, and more hydroprocessing for increased yields [14]. While there has been increased interest in using hydrogen as a fuel, high levels of hydrogen have been used in some applications such as boilers and fired heaters for many years. In the production of ethylene cracker using ethane as the feedstock, the off-gas produced is 70-85 vol% H_2 and is then used as the fuel for the cracking furnaces [15].

However, there are important issues that need to be considered for new applications using high levels of H_2 in the fuel. Some of these issues include: a higher potential for leaking from the fuel delivery system, very wide flammability range, higher flame speed, lower heating value on a volume basis, less air required per unit heating value, and higher adiabatic flame temperature compared to most common hydrocarbon fuels. A potential problem with a higher flame speed is a higher propensity to flashback in a premixed system. Another potential downside to using hydrogen for combustion is increased NOx emissions when air is the oxidant because of the increased adiabatic flame temperature. These issues impact the design of the combustion system which means that it is not necessarily a simple conversion from an existing hydrocarbon fuel to a fuel containing high levels of hydrogen. This includes the fuel delivery system, burner design, heat transfer, and pollution emissions, among others.

This paper provides an overview of the combustion of fuels containing high concentrations of hydrogen up to pure hydrogen. It will discuss the key considerations when designing a combustion system for high hydrogen fuels, including potential problems. It will also include some example applications of using high hydrogen combustion.

2. Hydrogen Combustion

Hydrogen has some unique properties compared to common hydrocarbon fuels such as methane and propane. Some of the more important differences are discussed in this section.

2.1 Heating Value

Hydrogen has a very high heating value on a mass basis and a very low heating value on a volume basis because it is a very light molecule. Table 1 shows higher heating values for some common fuels. Hydrogen's low volumetric heating value means much higher volumetric flow rates are required for a given heating rate compared to other common fuels. Higher volumetric flows means higher fuel pressures for fixed fuel injector outlet holes.

Table 1: Lower heating values of common fuels [20].

Gas	Btu/lb	Btu/scf
Methane (CH_4)	21,495	912
Propane (C_3H_8)	19,937	2,385
n-Butane (C_4H_{10})	19,679	3,113
n-Pentane (C_5H_{12})	19,507	3,714
Ethylene (C_2H_4)	20,275	1,512
Propylene (C_3H_6)	19,687	2,185
Hydrogen (H_2)	51,625	274.6
Carbon Monoxide (CO)	4,347	321.9

2.2 Flame Speed

Hydrogen has a high flame speed compared to many other gaseous fuels. Table 2 shows the laminar flame speeds for some common fuels.

Table 2: Maximum laminar burning velocities of common fuels [16, pp. 580-1].

Gas	ft/s	cm/s
Methane (CH_4)	1.37	44.8
Propane (C_3H_8)	1.41	46.2
n-Butane (C_4H_{10})	1.37	44.9
n-Pentane (C_5H_{12})	1.31	43.0
Ethylene (C_2H_4)	2.24	73.5
Propylene (C_3H_6)	1.56	51.2
Hydrogen (H_2)	9.91	325
Carbon Monoxide (CO)	1.58	52.0

2.3 Ignition

Hydrogen has a lower ignition temperature than methane but a higher ignition temperature compared to many other gaseous fuels. Table 3 shows the minimum ignition temperatures in air for some common fuels.

Table 3: Minimum Ignition temperatures in air for some common fuels [17].

Gas	°F	°C
Methane (CH_4)	1170	632
Propane (C_3H_8)	919	493
n-Butane (C_4H_{10})	761	405
Hydrogen (H_2)	1062	572
Carbon Monoxide (CO)	1128	609

As seen in Table 4, H_2 has a very low minimum ignition energy so it is easily ignited with a minimal spark. This is a good characteristic when ignition is desired but a not so good when trying to prevent ignition. It is known that static electricity can easily ignite H_2.

Table 4: Minimum spark ignition energy in air at 1 atm pressure and stoichiometric conditions for some common fuels [18].

Gas	10^{-4} J
Methane (CH_4)	4.7
Propane (C_3H_8)	3.05
n-Butane (C_4H_{10})	7.6
n-Pentane (C_5H_{12})	4.9
Hydrogen (H_2)	0.2

2.4 Adiabatic Flame Temperature

Hydrogen has a relatively high adiabatic flame temperature compared to many other gaseous fuels as shown in Table 5.

Table 5: Adiabatic flame temperatures of common fuels [19].

Gas	°F	°C
Methane (CH_4)	3542	1950
Propane (C_3H_8)	3610	1988
n-Butane (C_4H_{10})	3583	1973
Ethylene (C_2H_4)	3790	2088
Propylene (C_3H_6)	3742	2061
Hydrogen (H_2)	3807	2097
Carbon Monoxide (CO)	3826	2108

Figure 1 shows how the adiabatic flame temperature varies as a function of the equivalence ratio, with the peak close to an equivalence ratio of 1.0 (stoichiometric conditions) with both the air and fuel initially at 77°F and atmospheric pressure before combustion.

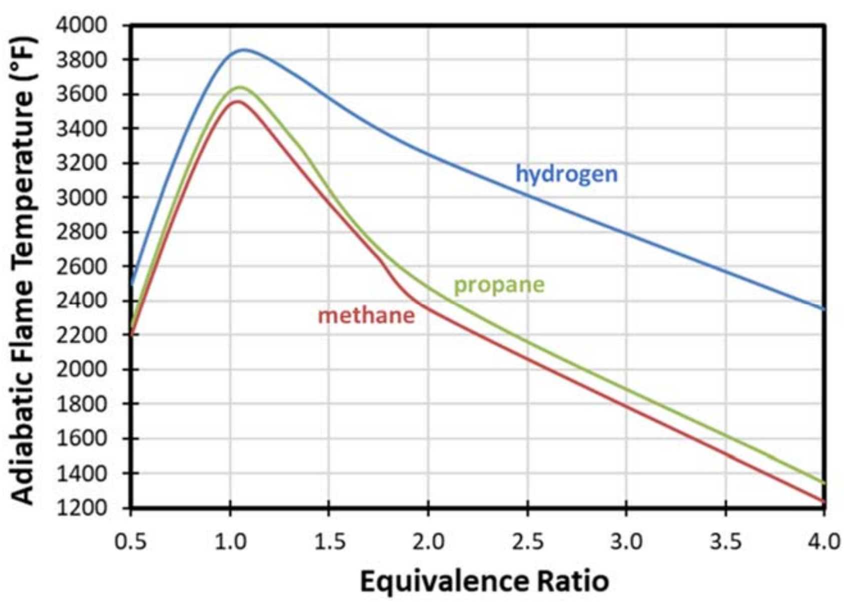

Figure 1: Adiabatic equilibrium flame temperature vs. equivalence ratio for air combusted with H_2, CH_4 and C_3H_8 [19].

Figure 2 shows how the adiabatic equilibrium flame temperature increases as the volume fraction of hydrogen increases in a CH_4-H_2 blend, with the peak at pure H_2. The adiabatic equilibrium flame temperature also increases with the air preheat temperature which ranges from 77 to 1500°F.

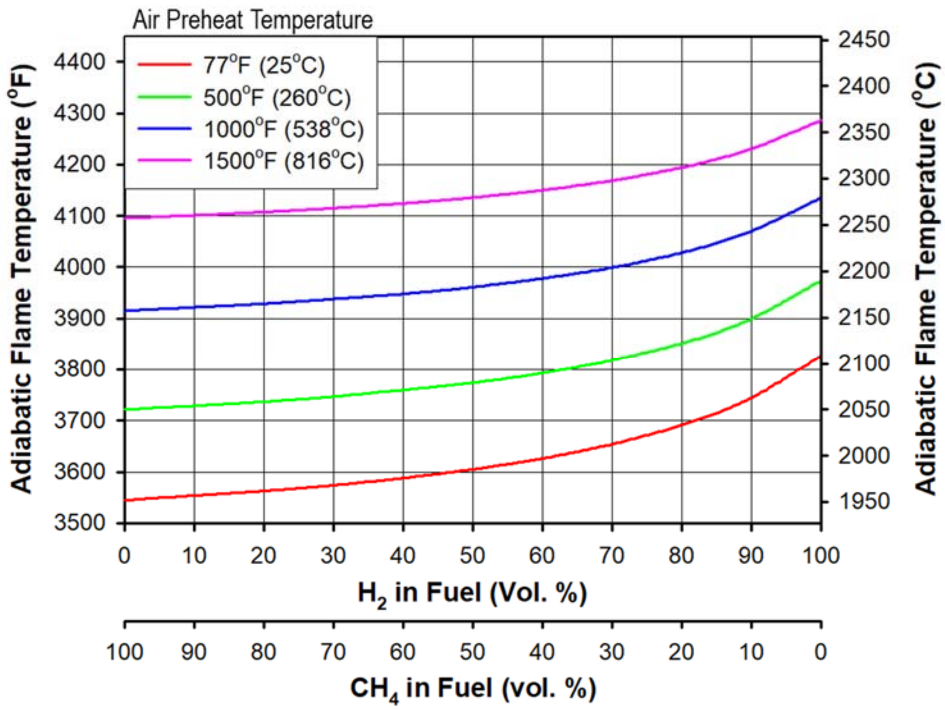

Figure 2: Adiabatic flame temperature for blends of CH_4 and H_2 as a function of air preheat temperature [19].

2.5 Flammability Limits

Hydrogen has wide flammability limits compared to many other gaseous fuels as shown in Figure 3.

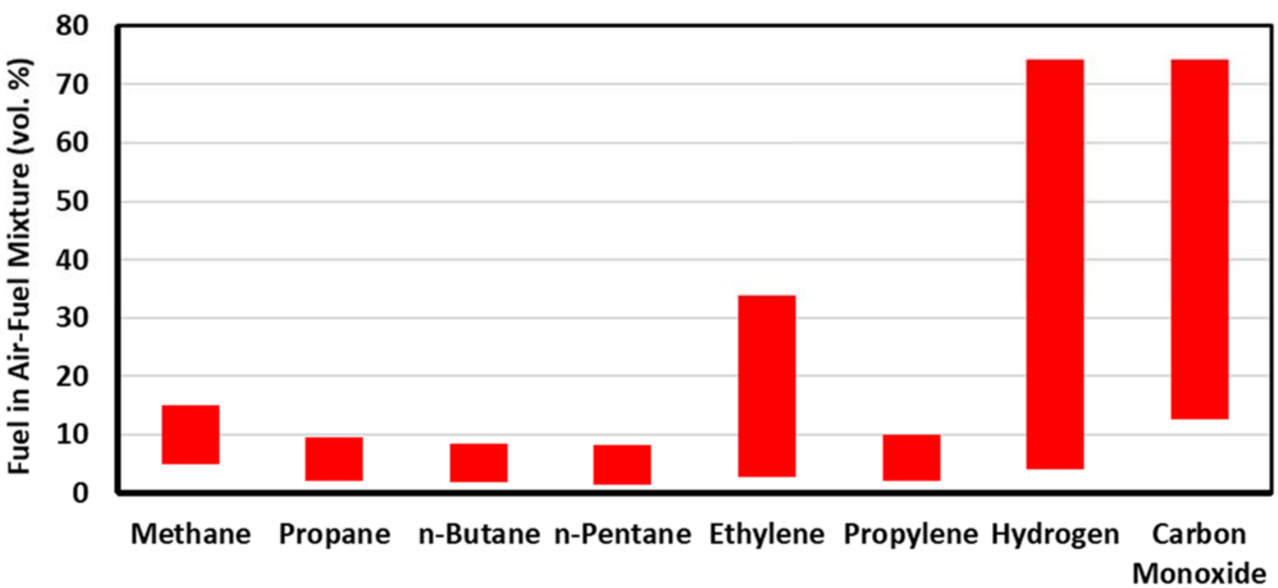

Figure 3: Flammability limits for common gaseous fuels [20].

2.6 Combustion Air Requirements and Flue Gas Volume

Table 6 shows that hydrogen requires considerably less combustion air, normalized to the firing rate, than many common gaseous fuels. The flue gas produced is comparable to most other fuels.

Table 6: Combustion air requirements and wet flue gas products for stoichiometric combustion on an LHV basis (calculated from [20]).

Gas	scf combustion air / MMBtu fuel	scf flue gas / MMBtu fuel
Methane (CH_4)	10,439	11,535
Propane (C_3H_8)	9,979	10,818
n-Butane (C_4H_{10})	9,939	10,742
n-Pentane (C_5H_{12})	10,253	11,061
Ethylene (C_2H_4)	9,444	10,106
Propylene (C_3H_6)	9,803	10,490
Hydrogen (H_2)	8,667	10,488
Carbon Monoxide (CO)	7,394	8,947

2.7 NOx Emissions

Due to hydrogen's higher flame temperature compared to other fuels, it would be expected to produce more thermal NOx emissions. However, prompt and fuel NOx are eliminated with pure H_2, since there are no carbon-based molecules in the fuel or oxidizer. Some detailed CFD modeling [21] showed the predicted NOx was comparable with pure H_2 compared to the base case in a fired heater [22]. The elimination of prompt NOx counteracted the increase in thermal NOx using H_2.

Figure 4 shows the predicted NO emissions for the equilibrium stoichiometric combustion of H_2, CH_4, and C_3H_8 with air increase rapidly with temperature. This is due to increased thermal NOx.

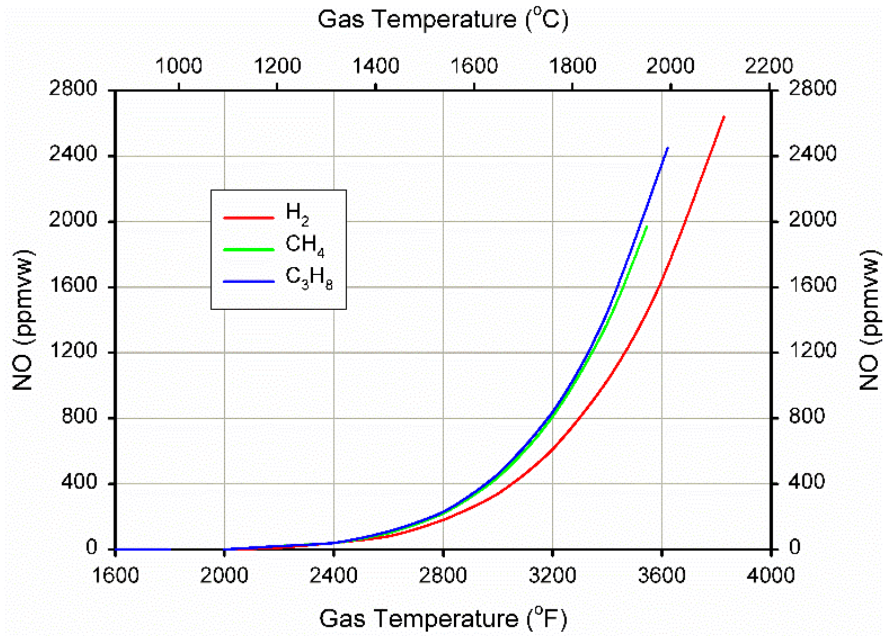

Figure 4: Predicted NO emissions (ppmvw) as a function of gas temperature for the equilibrium stoichiometric combustion of H_2, CH_4, and C_3H_8 with air [23].

Figure 5 shows the peak predicted NOx for H_2, CH_4, and C_3H_8 occurs at about an equivalence ratio of 0.8, with the values for H_2 being significantly higher than for CH_4 and C_3H_8. The reason for the peak near an equivalence ratio of 0.8 is the combination of higher flame temperature and excess O_2 available to combine with N_2 to form NOx.

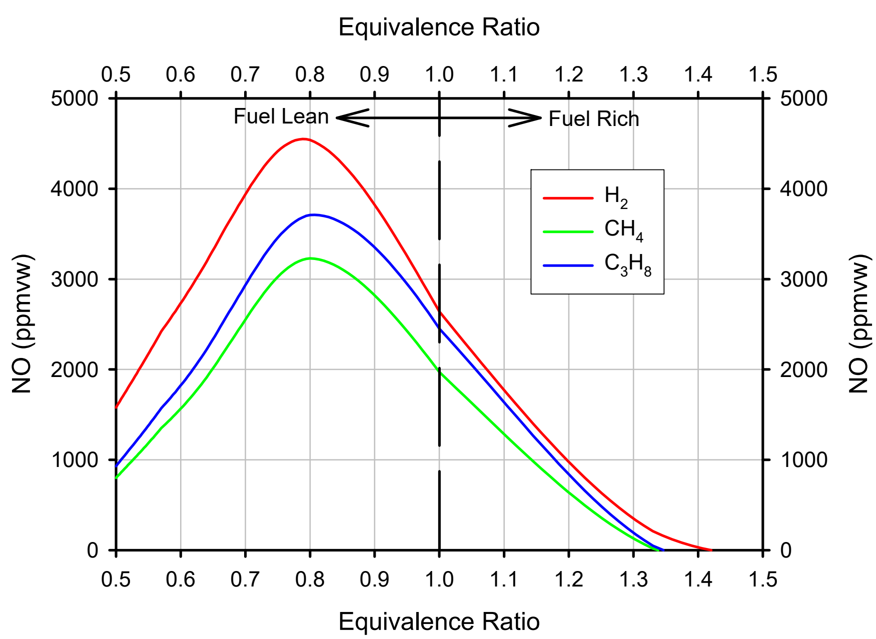

Figure 5: Predicted NO emissions (ppmvw) as a function of equivalence ratio for the adiabatic equilibrium combustion of H_2, CH_4, and C_3H_8 with air [23].

Figure 6 shows the predicted NO emissions increase for CH_4-H_2 blends as the fraction of H_2 in the blend increases.

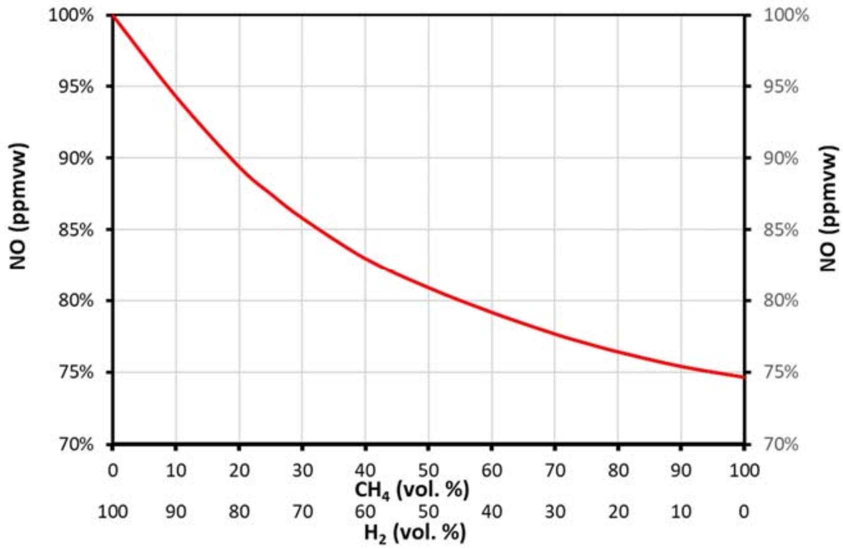

Figure 6: Predicted NO emissions (normalized to predicted NOx for 100% H_2) as a function of the fuel blend (CH_4-H_2) composition for the adiabatic equilibrium combustion with air [23].

3. Potential Advantages of Hydrogen Combustion

An important advantage of using hydrogen as a fuel is that the combustion products do not contain carbon dioxide. However, if the hydrogen is generated by conventional steam-methane reforming, then CO_2 is typically a by-product of the hydrogen production process. However, if the hydrogen can be produced using renewable energy, then it is possible to minimize or even eliminate CO_2 generation depending on the H_2 production process.

Another benefit related to emissions is that the absence of carbon in the fuel means no soot (smoke), carbon monoxide, or unburned hydrocarbons [24].

Since hydrogen requires less combustion air per unit firing rate, it may be possible to increase a burner's firing capacity less expensively using hydrogen than some of the alternative methods. In many cases, the limit on increasing the firing rate of an existing burner is the combustion air capacity. While it is usually relatively easy to get more fuel flow by increasing the size of the fuel injector holes, it may not be very easy to increase the combustion air capacity. One option to increase the air capacity is to add a fan for a natural draft system or increase the fan capacity in a forced draft system. Another option for a natural draft system is to increase the burner throat diameter with a new burner tile or to increase the heater draft. The latter may introduce some new issues that need to be considered.

4. Potential Challenges of Hydrogen Combustion

There are potential challenges of using fuels with high concentrations of hydrogen which are considered in this section.

4.1 Safety

Safety is an important consideration for any technology. As previously discussed, hydrogen has a considerably higher flame speed. This makes it much more susceptible to flashback in a premix burner compared to conventional fuels. This means the turndown (ratio of highest firing rate to lowest firing rate) in premix burners may be significantly reduced if high hydrogen fuels will be used. Specific burner designs may not be able to handle high H_2 fuels.

Another unique consideration is that because H_2 has low viscosity and molecular weight, it is much more likely to leak out of a fuel delivery system than other fuels [25]. That combined with its high flammability range and low energy required for ignition make it more likely to cause a fire if the leaking H_2 finds an ignition source. Electrical enclosures may need to be replaced with those specifically designed for high H_2 environments. Hydrogen embrittlement is another potential concern for the fuel delivery system [26].

4.2 Pollution Emissions

As stated above, while some pollution emissions such as carbon monoxide and carbon dioxide would be eliminated by using pure H_2 as a fuel, it is possible that NOx emissions could increase due to the higher flame temperatures [27]. However, as will be shown in Design Considerations, there may be some mitigating factors that could reduce NOx emissions.

Another pollutant that might be increased is noise [27]. This could be due to the higher pressures for high hydrogen fuels compared to other fuels. Some burner designs must operate on a wide range of fuels including both no/low and high H_2 concentrations. In those cases, the volume flow rates will be much higher for the high H_2 fuels because of H_2's low volumetric heating value. Noise can usually be mitigated with the proper fuel injector design and selection of sound-reducing equipment such as mufflers for process burners.

5. Design Considerations

This section is not intended to be exhaustive but rather representative of some of the issues that should be considered when designing a high hydrogen combustion system. Design considerations will depend on whether the installation is brand new or a retrofit.

The Wobbe index is defined as:

$$\mathrm{WI} = \frac{\mathrm{HHV}}{\sqrt{\mathrm{SG}}}$$

where HHV = higher heating value (Btu/scf) and SG = specific gravity. The WI can be used to compare fuels to determine potential differences in flow characteristics through a piping system. If the Wobbe indices for two fuels are similar (within approximately 5% [28]), then no changes to the gas tips should be needed when switching between the fuels. Table 7 shows the WI for various fuels. The WI for hydrogen is significantly different than for the other fuels which means the flow characteristics will be different when switching from another fuel to hydrogen. Mukherjee and Singh recommend conducting a detailed study of the entire combustion system before switching to a high hydrogen fuel [29].

Table 7: Wobbe index of various fuels (calculated from [20]).

Gas	SG	HHV (Btu/scf)	WI
Methane (CH_4)	0.554	1,013	1,361
Propane (C_3H_8)	1.522	2,592	2,101
n-Butane (C_4H_{10})	2.007	3,373	2,381
n-Pentane (C_5H_{12})	2.491	4,017	2,545
Ethylene (C_2H_4)	0.969	1,613	1,639
Propylene (C_3H_6)	1.453	2,336	1,938
Hydrogen (H_2)	0.070	325.0	1,228
Carbon Monoxide (CO)	0.967	321.9	327.3

5.1 Fuel Considerations

As previously discussed, hydrogen is more likely to leak compared to other fuels so more consideration is needed for example, for valve packings and seals. It may be preferred to weld joints to minimize the chance for leaks. NFPA 2 provides recommendations for hydrogen piping systems [30]. Under conditions of elevated temperature, pressure, or applied stress, hydrogen embrittlement of metals can be a problem [31] so consultation with a metallurgist is recommended to determine appropriate materials of construction for the fuel delivery system. Velocities through an existing system designed for another fuel like natural gas will be much higher for hydrogen. This could impact fuel flow meters that measure velocity such as vortex shedding and Coriolis meters.

How a combustion system is started may be important if a more conventional fuel like natural gas is used at startup before switching to hydrogen. This might occur when the hydrogen is produced on site, for example in an SMR. Burners designed to fire on hydrogen may have to start up initially on natural gas until the reforming process has been established and hydrogen is being produced. This could mean that burners would have to be capable of firing on both conventional fuels and on hydrogen. As shown, the combustion characteristics between hydrogen and other fuels can be significantly different, so this could complicate the burner design and system operation.

5.2 Combustion Air System

Hydrogen requires significantly less combustion air than traditional hydrocarbon fuels (see Table 6). This means less power will be required to run the combustion air fan for a given firing rate. As previously discussed, using hydrogen in natural draft burners provides an opportunity to increase the capacity without the addition of a forced draft fan.

5.3 Flame Detection

Hydrogen produces a weaker signal for the flame rectification circuit used in flame rods that are commonly used in pilots. On the other hand, hydrogen produces a very strong ultraviolet signal that is generally easily detected by ultraviolet flame scanners. The potential positive benefit is that flame sighting of UV scanners may be less challenging and that hydrogen flames may be able to be seen through more dust on the scanner lens before needing to be cleaned, compared to conventional fuels. Another factor is the flame flicker frequency with hydrogen is different than for other fuels, which can impact flame scanners trying to distinguish between flames and hot surfaces.

5.4 Burners

Again, related to fuel gas velocity, fuel injectors will likely need to be changed if retrofitting existing burners designed for another fuel like natural gas. This is similar to what needs to be done when retrofitting a propane barbeque grill to run on natural gas. The fuel injection holes (ports) may need to be larger when using high hydrogen fuels, compared to most other common gaseous fuels. The actual impact on retrofitting existing burners is very dependent on the burner design.

5.5 Heat Transfer

There are some factors related to heat transfer to consider when switching from a hydrocarbon fuel to hydrogen. The first is the impact on flame length. In general, hydrogen flames are shorter than hydrocarbon flames, for a fixed outlet velocity, due to the higher flame speed and reactivity of hydrogen. However, if switching from another fuel to hydrogen and keeping the same burner tip fuel injector holes, the outlet velocity of a high hydrogen fuel will be higher than for most other fuels. This will likely mitigate the effect of shorter flames with hydrogen.

A second factor to consider is the radiation heat transfer. On the one hand, the flame temperature is likely to increase significantly, assuming everything else is approximately the same because of H_2's higher adiabatic flame temperature (see Table 5). Since radiation is dependent on the fourth power of the absolute temperature, radiation could be increased. On the other hand, since there is no carbon in the fuel, there would be no soot formation with pure H_2. That means a hydrogen flame would not have any soot radiation, which can be significant for hydrocarbon fuels.

5.6 Pollution Emissions

As previously shown, assuming all variables are essentially the same except for fuel composition, the NOx emissions could increase significantly when switching to a high hydrogen fuel. However, there are some potential mitigating factors that could reduce the impact on NOx. For example, because hydrogen has such wide flammability limits, it may be possible to run parts of the flame much more fuel lean and much more fuel rich compared to typical fuels. Both of these tend to reduce NOx emissions. Also, it may be possible to run higher levels of internal flue gas recirculation (iFGR) with hydrogen without causing flame instabilities that would likely occur using traditional fuels at higher iFGR levels. Higher levels of iFGR would reduce NOx emissions.

Using hydrogen instead of hydrocarbon fuels eliminates carbon in the fuel which eliminates soot, carbon monoxide, carbon dioxide, and unburned hydrocarbon emissions. This makes gas sampling simpler, although the exhaust gas conditioning system may need to be reviewed. Those conditioning systems clean, dry, and cool the gas sample before it goes to the analyzers. Because pure hydrogen produces much more water than hydrocarbon fuels, the water removal capacity in the conditioning system may need to be increased.

Another potential benefit of using hydrogen is that the combustion product volume flow rate is reduced compared to more traditional fuels. Again, this would reduce the power needed for any exhaust draft fans and provide the potential for increasing the firing rate without increasing the exhaust gas flow capacity.

6. Fired Heater Examples

The impact of hydrogen in the fuel gas on overall heater operation was investigated for different fuel gas mixtures by Lowe et al. [32] and Mukherjee and Singh [29]. Both studies were conducted with the FRNC 5PC software. For both studies, the fuel flow was changed to achieve the same absorbed heat by the process fluid. Both studies showed that the duty of the radiant section increased by 2.5 to 3% with a high H_2 fuel. Mukherjee and Singh also showed the overall efficiency of the heater increased by 2.2% when increasing the hydrogen content in the fuel gas from 10% to 90%. These studies were conducted on a well-stirred firebox with rough assumptions, without any detailed view on the burner. To analyze the detailed heat distribution in the furnace, a detailed computational fluid dynamic (CFD) analysis is required that also includes the details of the burner.

A 3D CFD simulation was conducted to study the impact of hydrogen content in the fuel gas on overall heater performance. A John Zink test furnace with two natural draft, ultra-low NOx COOLstar®-18 burners was used as the modeling case. This model represents a typical ethylene cracking application with floor burners fired against the wall. The geometry comprised the entire furnace including the cooling-tubes as well as a detailed model of both burners (see Figure 8). The computational mesh consisted of approximately 13×10^6 finite volume cells. Turbulence was modeled using the k-ε model with two-layer all y+ wall treatment. Combustion was modeled with a hybrid eddy breakup combustion model.


(a) (b)

Figure 7: CFD model of 2 burners in a cracking furnace simulator: (a) side view, (b) front view.

Three cases were simulated (see Table 8). The burner geometry was designed for the base case which had an H_2 content of 28% in the fuel gas. For the other two cases, only the fuel gas composition was changed by increasing the hydrogen content to 65% and 100%. The burner operating conditions and the burner geometry remained unchanged. As a result, the fuel gas pressure increased with increasing amounts of H_2 in the fuel to keep the heat release constant.

Both graphs in Figure 8 show the local normalized and absolute heat fluxes over the normalized height of the furnace. The graph with the normalized heat flux shows the location of the peak heat flux shifted closer to the burner with an increasing amount of H_2 in the fuel gas. The incident heat flux, shown in Figure 8b, indicates the total amount of heat transferred to the coils increased with an increasing amount of hydrogen in the fuel gas. Both effects are related to the higher adiabatic flame temperature and higher combustion velocity of hydrogen. So, more heat is released in closer proximity of the burner which leads to higher thermal radiation. The reduction in flame height is also confirmed by the values of the flame length shown in Table 8. Here the results show a reduction in flame height of 4.3 ft between the base case and the 100% H_2 case. The flame envelope is defined as the iso-contour of 3.5 mol% O_2. The typical definition of the flame envelope of 2000 ppm CO is not applicable for this study since no CO emissions are generated when firing 100% H_2. The total absorbed heat in the radiant section increased by 4.4% between the base case and the 100% H_2-case. So, less heat transferred to the convection section, even if the bridgewall (top of the radiant section) temperature increased with an increasing percentage of H_2.

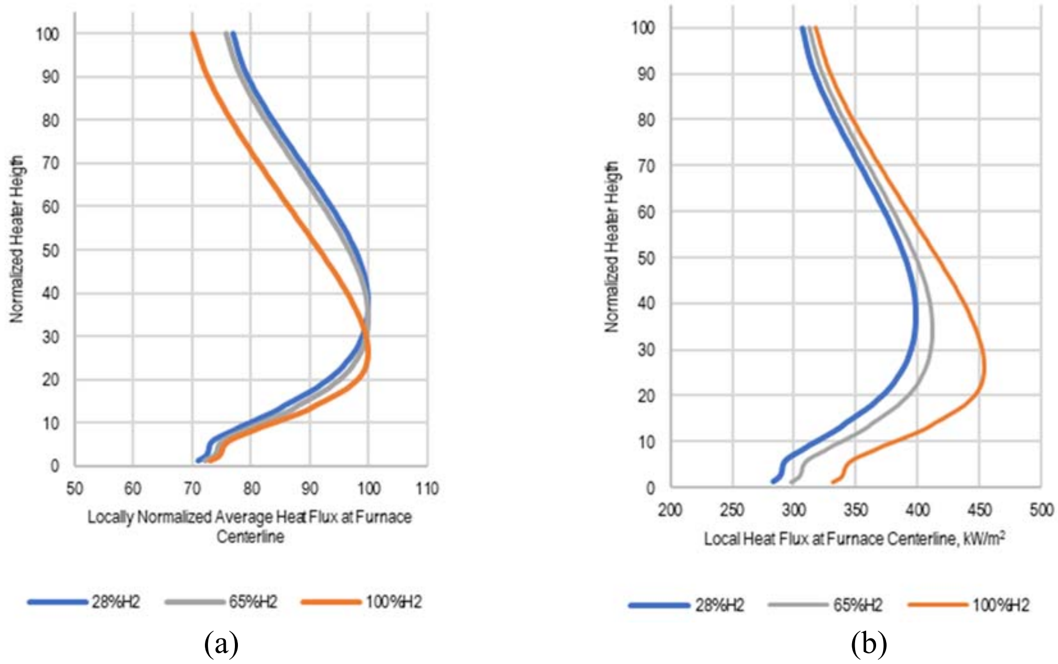

Figure 8: CFD results as a function of normalized heater height for (a) locally normalized average heat flux at the heater centerline and (b) local heat flux at the heater centerline.

Table 8: Conditions for the 3 cases modeled.

	28% H_2, 69% CH_4, 2% C_2+, 1% N_2 (Base Case)	65% H_2, 35% CH_4	100% H_2
Chemical heat release, MMBtu/hr	22.7	22.7	22.8
Relative radiant section duty, %	39.8	41.0	44.2
Floor temp., °F	1981	2017	2089
Bridgewall temp., °F	2053	2057	2088
Flame length (3.5 mol% O_2), ft	15.1	13.3	10.8
Max. heat flux, MMBtu/ft^2/hr	0.126	0.131	0.144
Relative heat flux elevation, %	37.8	35.0	25.9

This study shows the hydrogen content has a significant impact on the heat distribution inside the firebox. Additionally, it has been shown the absorbed heat of the radiant coils as well as the bridgewall temperature is impacted by the amount of H_2 in the fuel gas. It is recommended that the burner manufacturer be consulted before changing the fuel gas composition, since the fuel gas impacts the burner design and a change in burner tips might be necessary to ensure stable burner operation and an acceptable heat transfer distribution.

Conclusions

Using fuels with high hydrogen concentrations has the potential to dramatically reduce CO_2 emissions compared to conventional hydrocarbon fuels, depending on how the hydrogen is produced. Hydrogen has many unique characteristics, such as a higher flame speed and adiabatic flame temperature, compared to conventional hydrocarbon fuels. There are many potential challenges, such as safety and operational issues, that need to be considered when using high hydrogen fuels. There are also many issues related to the design that need to be considered. In general, depending on the specific application, the transition from typical hydrocarbon fuels to hydrogen may be possible with relatively little change in performance. A thorough analysis is recommended before making such a change.

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