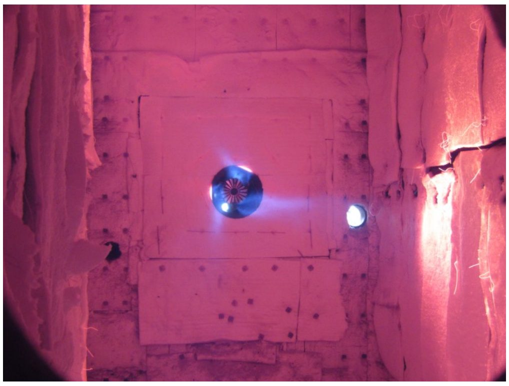
Practical Considerations for Firing Hydrogen Versus Natural Gas

By John Guarco, Bob Langstine, and Michael Turner

Rising fuel costs and new regulations requiring carbon footprint reductions continue to pressure today's steam generation market. New regulations require steam generators to reduce their carbon monoxide (CO) and carbon dioxide (CO_2) emissions. The two main methods to reduce CO and CO_2 emissions are to either capture and sequester the carbon in the fuel gas or remove carbon from the fuel before firing. Removing carbon from the fuel is becoming the more cost-effective method. Removal of the carbon prior to firing involves reforming natural gas — mainly methane (CH_4) — and capturing the carbon atom while utilizing the hydrogen (H_2) atoms as a fuel source. Removing carbon before combustion eliminates the need to outfit each boiler with costly equipment to capture and sequester the carbon during firing. Fuel cost instability pushes end users to consider alternative fuel sources they may already have, such as H_2 left over from various reforming and refining processes. Instead of flaring or releasing this excess H_2, it can be injected into the fuel gas stream to supplement the main fuel supply. Applying the proper expertise and experience, burning H_2 in steam generation systems can significantly reduce operating fuel costs while also helping to meet new carbon emissions regulations.

Burner Design Considerations



Burner designs must be evaluated for compatibility with H_2 firing to ensure proper and safe operation. The combustion characteristics of H_2 are vastly different from those of natural gas. The flame speed in H_2 combustion is approximately 1.7 metres per second, while the flame speed of natural gas is significantly slower at only 0.4m/s. H_2 firing has a higher stoichiometric adiabatic flame temperature of 2,182°C, while natural gas has an adiabatic flame temperature of 1,937°C (these measurements are cited from "Combustion – Second Edition" by Irvin Glassman (1987). These significant differences in combustion characteristics require engineers to evaluate the materials used in burner construction and the type of burner used.

Typical burner construction includes various metal components and a refractory throat or tile. The increased flame temperature of H_2 requires upgrading the steel used for nozzle construction, throat construction, and flame stabilizers to a higher grade stainless or alloy. Refractory used within the burner should be carefully evaluated and its composition modified to withstand the elevated temperatures characteristic of H_2 firing.

The steel used in burners firing H_2 should not be susceptible to hydrogen embrittlement and high-temperature hydrogen attack. Both phenomena can prematurely degrade an improperly chosen steel, leading to early failure of the burner parts.

Hydrogen's flame speed, which is nearly five times that of natural gas, is a fundamental cause of concern when evaluating burner design. Burner designs that utilize lean premix, premix, or rapid premix designs are not suited for a fuel stream that varies in H_2 composition. As the composition of H_2 increases in the fuel stream, these types of burners become more susceptible to flashback. Flashback occurs when the gas velocity exiting the burner nozzle is slower than the flame speed in a premixed application. Damage to the burner components can result when flashback occurs.

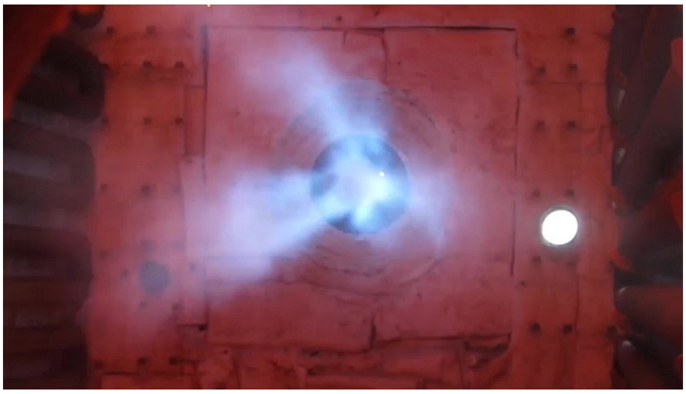
Emission Considerations

Another essential topic when considering H_2 firing is the impact on burner emissions. Hydrogen's high flame propagation speed allows the combustion process to occur more rapidly than natural gas. This rapid combustion process releases the combustion energy in a small area, leading to localized elevated near-flame region temperatures, which compound the effect of the inherently high adiabatic flame temperatures on NO_X emission rates. Any region with elevated temperatures above 1,371°C is conducive to NO_X formation. Field and test facility data have shown that standard low-NO_X burners firing H_2 typically exhibit an increase in NO_X emission rates by up to a factor of three.

Flue gas recirculation (FGR), steam injection, ultra-low-NO_X (ULN) burner technology, or some combination of those approaches are typically required to decrease NO_X. FGR is the process that diverts a portion of the flue gas exiting the boiler (typically after the economizer) and introduces it into the combustion air supply. The spent combustion products dilute the combustion air supply, which lowers the peak flame temperature during combustion. Small quantities of carefully placed steam injection can also help control NO_X by cooling the flame and introducing a small amount of inerting.

Staged ULN burners are another option to combat the increased NO_X emissions associated with firing H_2. These types of burners generally use both air and fuel staging to decrease peak flame temperature. Properly staged fuel increases the amount of furnace gas entrained into the fuel stream prior to interacting with the air. Entraining furnace gas into the fuel stream has a similar effect to the way FGR mitigates NO_X. Properly staging air within the combustion zone delays the mixing of the fuel and air, stretching the combustion process over the furnace's length. The drawn-out combustion process decreases overall peak combustion temperatures, thereby reducing NO_X formation.

There are essential differences between *staged* ULN burners and *premix* ULN burners. As explained earlier, premix ULN burners are typically not constructed of materials capable of withstanding H_2 firing, nor are they able to prevent flashback while firing high H_2 fuels.



The H_2 content in the fuel stream also has a significant impact on CO and CO_2 emissions. As H_2 replaces hydrocarbons in the fuel composition, the number of carbon atoms decreases. A fuel stream composed of 100% H_2 cannot generate CO nor CO_2 as a byproduct of combustion due to the lack of carbon in the combustion reaction. Therefore, the higher the H_2 content of a fuel, the lower the CO and CO_2 emissions. Please see the stoichiometric combustion reaction of a hydrocarbon-based fuel, natural gas, and the combustion reaction of pure H_2.

Equation 1 – Natural Gas Combustion Reaction:

$$CH_4 + 2(O_2 + 3.76N_2) = CO_2 + 2H_2O + 7.52N_2$$

Equation 2 – Hydrogen Combustion Reaction:

$$2H_2 + (O_2 + 3.76N_2) = 2H_2O + 3.76N_2$$

Boiler Impact Considerations

When considering a new fuel in a boiler, including H_2, a boiler impact study can highlight any impact on boiler performance. The combustion characteristics of H_2 can lead to changes in where and how radiative and convective heat transfer occurs within the boiler, which may adversely impact steam generation rate and steam temperatures.

Based on equations 1 and 2, the stoichiometric air requirement for natural gas is ~0.31 kg of air/MJ, and the stoichiometric air requirement for H_2 is ~0.24 kg of air/MJ, respectively; therefore, H_2 firing needs approximately 30% less mass flow of air as compared to natural gas. Furthermore, H_2 can operate with a lower excess air ratio than natural gas due to its higher flammability limit. A lower excess air ratio further reduces the required mass flow of air as compared to natural gas. H_2 firing also increases the furnace gas exit temperature (FEGT), primarily due to the higher flame temperatures.

When firing H_2, the resulting mass flow reduction through the boiler, combined with higher FEGT, can adversely impact the boiler's convective heat transfer portions, jeopardizing steam production and steam quality. However, adding mass flow to the system via external FGR can lower the FEGT and negate any adverse effects on convective heat transfer.

Instrumentation and Controls Considerations

When utilizing H_2 as a fuel source, the final topic to be considered is controls and instrumentation required for safe firing. Any burner designed to have a varying fuel composition spanning from natural gas to high H_2 content should have a fully metered combustion control system coupled with a Wobbe Index meter or specific gravity meter in some cases. The Wobbe Index meter monitors the varying fuel stream composition and provides the necessary input to the control system to properly adjust the fuel/air ratio control in the combustion control system. The inability to monitor the fuel stream composition and adjust the combustion control system to those changes can lead to a potentially unsafe, fuel-rich condition.

Knowledgeable personnel should also evaluate the fuel delivery equipment upstream of the burner for capacity constraints. H_2 requires three times the volumetric fuel flow compared to natural gas to provide the equivalent heat release. Personnel should also evaluate pipe size and engineered fuel train components to ensure proper operation with any fuel, particularly when used in any combination with H_2.

All current boiler operating codes require flame detection as a critical burner safeguard. When H_2 is present in the combustion process, it generates water vapor. As the H_2 content approaches 80% in the fuel stream, most flame scanners available today have difficulty distinguishing and verifying the flame due to the high level of water vapor present. Selecting the proper flame detection equipment is crucial.

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