Advanced Hydrogen Burner for Commercial and Industrial Applications

Sandeep Alavandi[1], Hamid Abbasi, David Cygan and John Wagner
GTI Energy, Des Plaines, IL 60018

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ABSTRACT

GTI Energy (GTI) is extending its 3D printed multi-venturi natural gas burner technology[2] to fire Hydrogen (H_2) blended natural gas. A 3 MMBtu/h laboratory prototype burner has been designed, fabricated and tested with 0, 10, and 20% H_2 in natural gas by volume. Detailed tests and measurements were carried out at GTI on an industrial scale furnace to demonstrate the key performance characteristics of this burner using a process air heating setup. The results show the tested burner: 1) Allowed operation at up to 6:1 turndown to heat process air directly or through a heat exchanger, 2) Provided very low carbon monoxide (CO) emissions of below 10 ppm over the entire range of firing rates and excess air levels tested, 3) Provided robust ignition and stable flames, and 4) Easily achieved oxide of nitrogen (NOx) levels of less than 40 ppm (corrected to 3% O2) at all 3 firing rates and on all fuel blends at specific excess oxygen (O2) levels. It is believed, the key performance characteristics of the burner, e.g. combustion air pressure requirements, turndown capability, ease of ignition, flame stability, and CO and NOx emissions would meet standard market requirements. GTI is currently pursuing design improvements to further reduce NOx emissions to ≤9 ppm over a turndown of 6:1 and plans to test the technology in a field environment for real-world feedback. Incorporating refinements based end user feedback should improve market attractiveness of the technology.

INTRODUCTION

H_2 gas is being pursued as a sustainable energy carrier, and blending H_2 into existing natural gas pipelines has been proposed to increase the output of renewable energy systems like large wind farms. If implemented with relatively low concentrations of less than 5%–15% H_2 by volume, this strategy of storing and delivering renewable energy to markets appears viable without significantly increasing risks associated with using the gas blend in end-use devices such as household appliances, reducing overall public safety, or degrading the durability and integrity of the existing natural gas pipeline network. However, the appropriate blending concentration may vary significantly between pipeline network systems and based on natural gas composition. The issues of increasing H_2 blending levels in pipeline gas and modifications needed for end-use equipment, from household appliances to industrial or power generation systems, have not been

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[1] salavandi@gti.energy

[2] Alavandi S., Abbasi H., Cygan D., Wagner J., Design and Development of Advanced 3-D Printed Burner for Process Heating Applications, American Flame Research Committee, September 25-27, 2023, Denver, CO.

adequately resolved in the industry. The current project aims to provide industrial-scale experimental data to address these concerns.

Ilbas et.al[3] studied laminar burning velocities of H_2-air and H_2-methane (CH4) mixtures. The results showed there are significant differences when operating with H_2 blends compared to CH4. Figure 1 shows the propagation velocity of a laminar flame front (also termed laminar burning velocity or flame speed) into unburned premixed gas and air for different H_2 concentrations in H_2/ CH4 mixtures at an equivalence ratio of 1.0 (i.e., no excess air or excess fuel). The addition of H_2 significantly increases the flame speed. The flame speed of 100% CH4 is 0.37 m/s, whereas for 100% H_2, it is 3 m/s, nearly an order of magnitude increase. This leads to a significantly increased risk of flashback (flame propagating into the upstream fuel-air mixing region) and overheating of the burner front components.

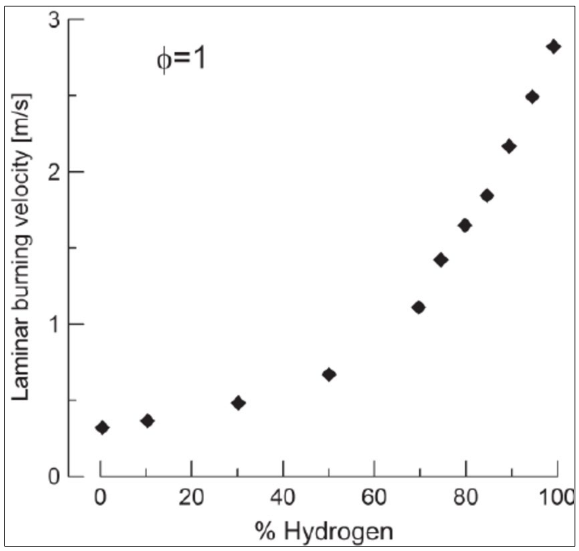

Figure 1. Comparison of laminar flame speed as a function of percent H_2 in the CH_4[2]

Chen et. al.[4] studied laminar flame speeds of H_2, natural gas and air mixtures. Figure 2 shows the impact of incremental changes in flame speed with increasing levels of H_2 blending in natural gas for equivalence ratios of 0.8 to 2.0. Large commercial and industrial equipment operate in the range of equivalence ratios from 0.65 to 1.0. Power generation and some building equipment fire in equivalence ratios from 1.0 to 2.0. The flame speed increment is the ratio of the 'increase in flame speed versus natural gas at a given H_2 blending percent' to the 'increase versus natural gas for 100% H_2. As the H_2 addition increases, the flame speed increases, which could

[3] Ilbas, M., Crayford, A., Yilmaz, I., Bowen, P. & Syred, N., Laminar burning velocities of H2-air and H2-methane-air mixtures: An experimental study, Int. J. H2 Energy 31: 1768–1779 (2006)

[4] Chen D., Qulan Z., Xiaoguang Z., Qinxin Z., Tongmo X. & Shi'en H., Experimental study on the laminar flame speed of H2/natural gas/air mixtures, Front. Chem. Eng. China, 4(4): 417–422 (2010)

significantly impact the combustion system. For example, their results show to match the total heat content, the volume of H_2 required is nearly three times that of natural gas.

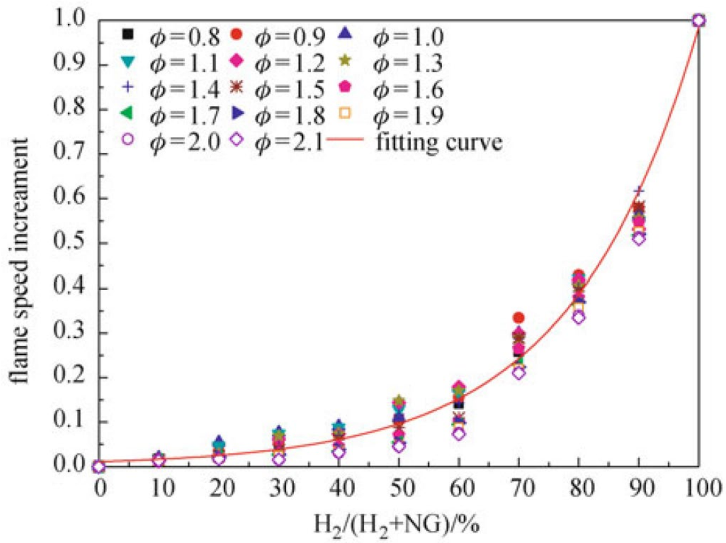

Figure 2. Incremental change in flame speed change with addition of H_2 to natural gas[3]

Zhao et.al.[5] investigated the influence of H_2 addition to pipeline natural gas. The heating value was found to show a declining linear trend as the H_2 percentage increases, but the Wobbe Index shows an inflection point at around 81% H_2 (Figure 3). Additionally, 100% H_2 was found to have the same Wobbe Index as a 35% H_2/65% natural gas mixture. However, the flame properties of these two fuels (e.g., flammability, flame speed, and flame temperature) are very different, leading to significant differences in combustion performance. This implies that, although the Wobbe Index predicts impacts on heat input, it cannot be the sole fuel interchangeability factor for combustion devices. Impacts on flame shape and profile, as well as emissions and turndown capability, are important to understand when using H_2 blends with natural gas.

GTI previously developed and tested a bench-scale 0.05 MMBtu/h 3D-printed burner design capable of operating efficiently and robustly with up to 40% H_2. The current research aimed to demonstrate a scaled-up 3 MMBtu/h burner with higher H_2 concentrations.

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[5] Yan Z., Vincent M. & Scott S., Influence of H2 addition to pipeline natural gas on the combustion performance of a cooktop burner, International Journal of H2 Energy, 44: 12239-12253 (2019)

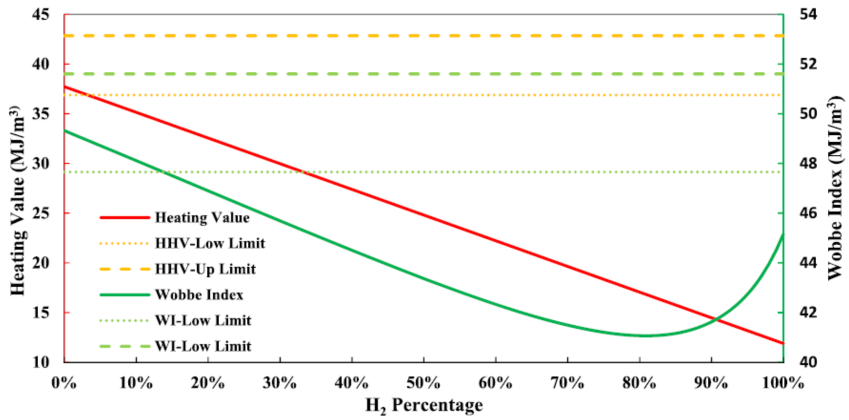

Figure 3. Impact on Wobbe Index and heating value with addition of H_2 in natural gas[4]

SAFETY

Blending H_2 with natural gas presents three main safety concerns:

1. Higher Flame Temperatures and Flame Speeds: Higher flame temperatures and speeds can cause overheating and flashback into undesired areas. Solutions include operating the burner at flow velocities above the flame speed or using non-premixed (diffusion flame) burners. For industrial applications, maintaining flame length and luminosity is crucial for safety and productivity. Proper controls, improved burner designs, and flame safety equipment can mitigate these risks.

2. Material Degradation: First, prolonged exposure to H_2 can make metals, especially high-strength steel, brittle and prone to fracture. H_2 atoms diffuse into the metal, pin dislocations, and cause brittleness. This issue is more severe in high-strength steels and nickel-titanium alloys, particularly in thick-walled components. Second, H_2 reacts with carbon at high temperatures to form methane, creating cavities in the metal. These cavities can coalesce into micro-cracks and eventually macro-cracks, reducing fracture toughness.

3. Fuel Leakage: H_2's wider flammability limits make it easier to ignite, increasing the risk of fire or explosion. Mitigation strategies include using welded joints or H_2-approved pipes and fittings. Forced venting with fans can help avoid combustible gas accumulation, and H_2's buoyancy helps it disperse quickly. Proper planning, maintenance, and leak detection are essential to prevent leaks and ensure safety.

3D PRINTED BURNER

The 3D-printed multi-venturi burner was developed at GTI and printed at Oak Ridge National Laboratory (ORNL). It had shown stable performance in earlier tests with NG, including superior air-fuel mixing, a uniform flame temperature profile, and over 6:1 turndown. The design is fuel-flexible, scalable, and modular, supporting various gases, including H_2. Its internal recirculation reduces NOx emissions and minimizes temperature and velocity gradients at the burner exit. The rapid fuel-air mixing ensures a robust flame and prevents flashback. Figure 4 shows the multi-venturi assembly of the burner that was 3D-printed.

Its key features are:

1. Self-Proportioning Air-Fuel Ratio: The burner self-proportions the air-fuel ratio amongst individual venturi nozzles over its turndown range.
2. Flame Profiling: Multiple nozzles allow for flame shaping to optimize heat transfer and minimize emissions.
3. Fuel-Staging Control: The design can concentrate the flame on specific sections, improving control and reducing NOx emissions.

TEST SETUP

The burner housing with the internal 3-D printed multi-venturi assembly was mounted directly on the GTI test furnace as shown in Figure 5 (left). The front section of the burner was on the other side of the flange and was placed inside the furnace. The air-fuel skid for controlling the flow of these gases, including both H2 and natural gas, is shown in Figure 5 (right). The fuel flowmeter and its location on the skid are shown in Figure 6.

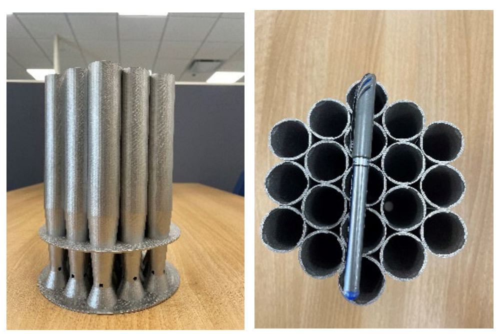

Figure 4. 3D printed multi-venturi assembly

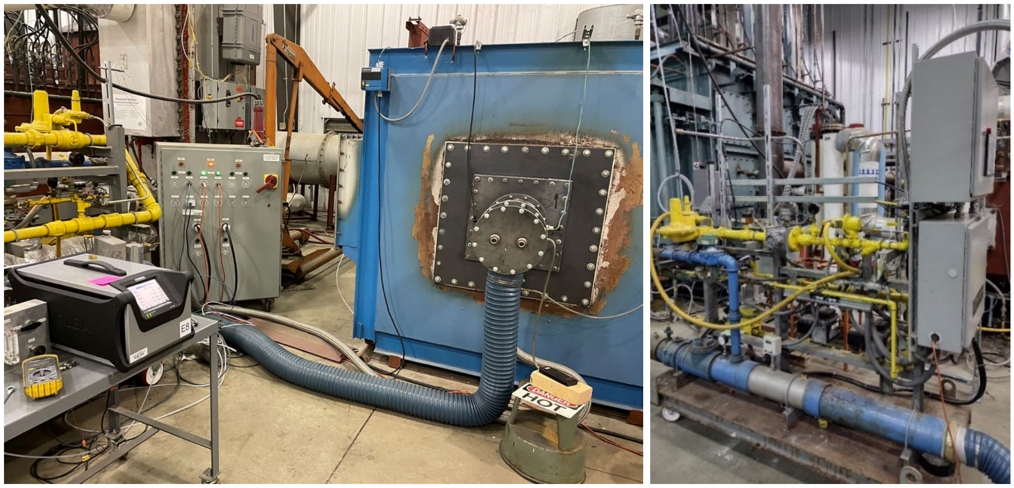

Figure 5. Test setup showing burner mounted on the furnace (left) and air-fuel skid (right)

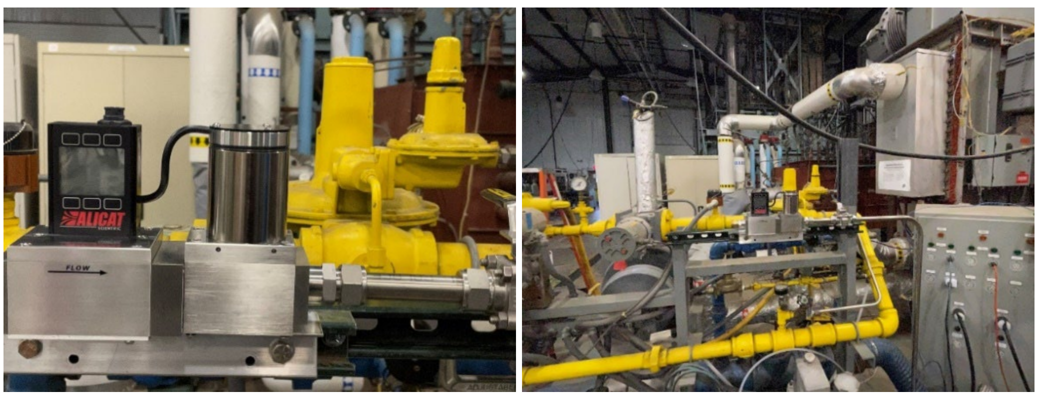

Figure 6. Flow meter mounted in fuel-air skid

The test set-up included all necessary instrumentation for controlling the flow of air and fuel to the burner including safety for operating H_2, measuring the pressures and flowrates, and measuring the composition of the post-combustion exhaust stream, including pollutants. Tests were conducted with natural gas and with 10 and 20% H_2 mixed with natural gas at three different firing rates (1, 2, and 3 MMBtu/h).

TESTS RESULTS

Figure 7 shows the plots of fuel pressure as a function of excess O_2 in the furnace exhaust for different H_2 blend levels at the 3 different firing rates tested. Natural gas is listed as NG here and elsewhere. Excess O_2 is a measure of how lean the furnace operates. Both flame and exhaust temperatures generally decrease as excess O_2 is increased because of dilution. The data show that fuel pressure starts with a negative value (i.e., below atmospheric) at the lowest excess air level and decreases further as excess air level is increased. This is true at all 3 firing rates (1, 2, and 3 MMBtu/h), with the suction being less at low firing rates (-0.5 to -5.0 inches of H_2O) and greater at high firing rates (up to -20 inches of H_2O). This is an indication that the venturi design is working as expected creating negative pressure at the venturi throats for fuel aspiration. The fuel is supplied through small holes in the throat of each the venturis. The higher the air flow rate, the higher the level of suction it generates at the throat of the venturis.

Figure 7 also shows that the fuel pressure is the lowest (or the burner generates the highest level of aspiration) when operating on 100% NG and the pressure is higher (less negative) as more H_2 is mixed in with the natural gas. This is because of the significantly lower volumetric flow of air required for H_2 combustion. The results show that this burner design should have enough aspiration to draw in enough fuel into the venturis irrespective of the firing rate or excess air level.

Figure 8 shows similar plots but for air pressure. As expected, the air pressure is lowest for the smallest firing rate and increases as the firing rate or the excess air level increases. Inlet air pressures vary from a low of about 2 inches of H_2O up to about 30 inches of H_2O column. The air pressure requirements are highest for firing on 100% natural gas and decrease as H_2 is added to the fuel. The burner fan has to work the hardest to provide air for 100% natural gas firing and less hard as H_2 is blended due to reduced air required for combustion and de-rating the burner firing leading to the reduced air requirements and hence lower pressure drop. This is because it takes more O2 (and therefore more air) to burn one Btu of CH_4 than it does to burn one Btu of H_2. However, in all cases the pressures are low enough that sufficient air can be provided at all firing rates and excess air levels with typical burner fans or blowers.

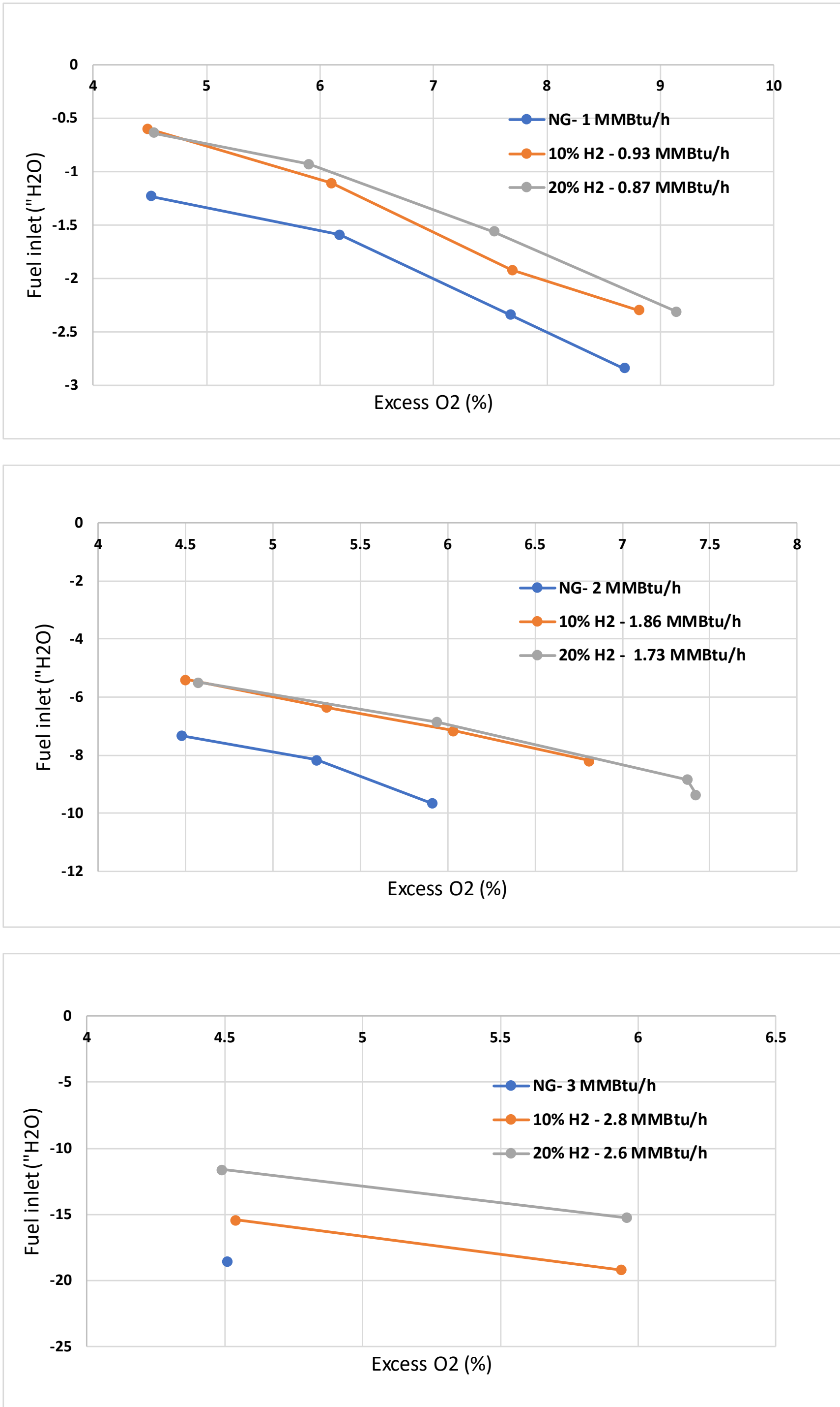

Figure 7. Variation of fuel side suction with excess O_2 (i.e., combustion air flow rate) for different firing rates and fuel blends. For 10 and 20% H_2 blending, the firing rate was de-rated.

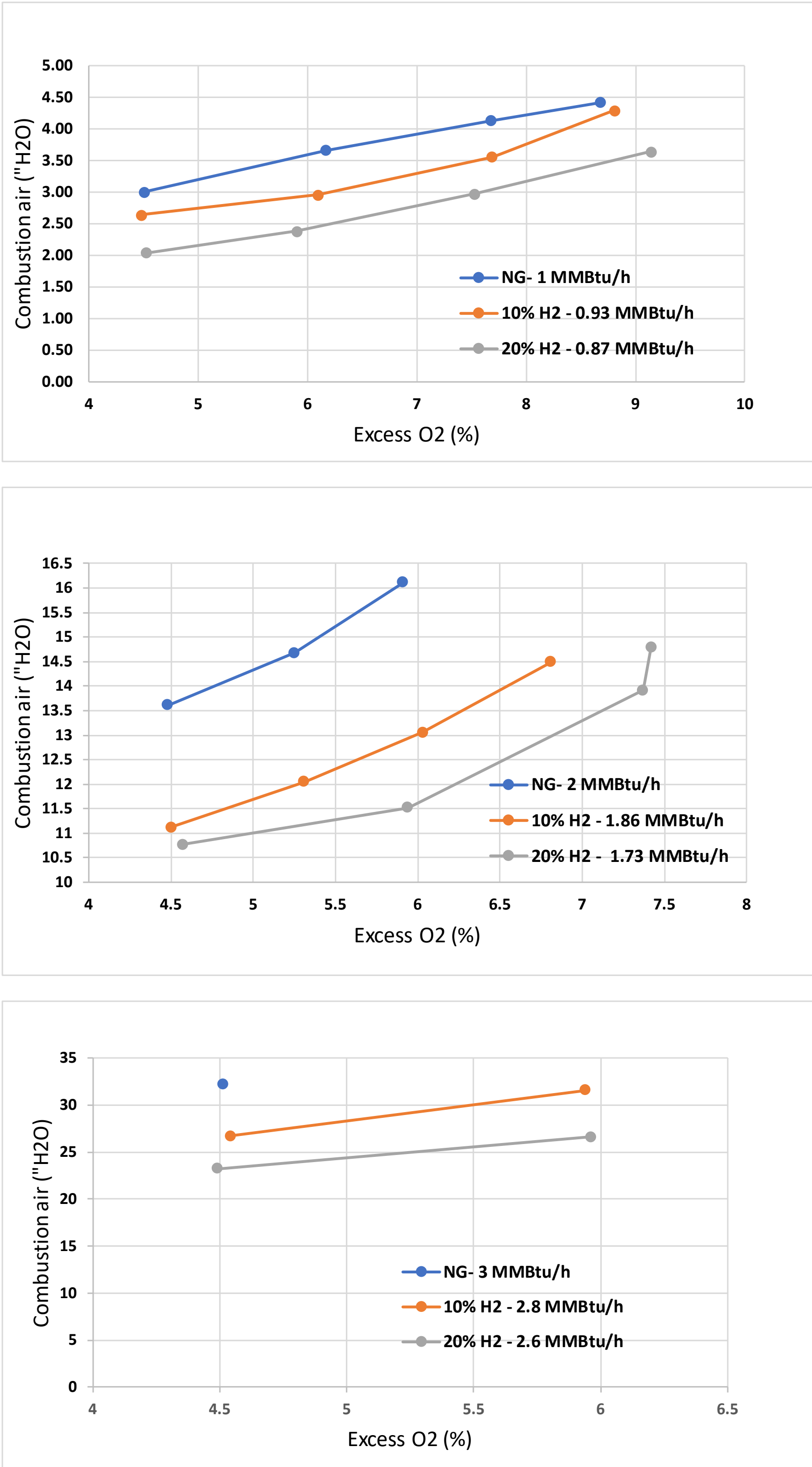

Figure 8. Variation of air supply pressure with excess O_2 (i.e., combustion air flow rate) for different firing rates and fuel blends. For 10 and 20% H_2 blending, the firing rate was de-rated.

Figure 9 shows the NOx concentration at the furnace exit at different firing rates and excess O_2 levels. As is common with premixed type natural gas burners, at all firing rates NOx decreased with increasing excess O_2 concentration because of decreasing flame temperature. This is an indication that the burner provides excellent fuel-air mixing at all firing rates and excess O_2 (i.e., air) levels. There are no anomolies in the data. All NOx values are corrected to a common 3% excess O_2 level to remove the effect of exhaust gas dilution with excess air when reporting NOx emissions. The results show that the NOx levels are highest at the lowest firing rate (as high as about 90 ppm) and are reduced as the firing rate goes up (down to about 40 or 45 ppm at the same O_2 level).

The reason for this behavior is most likely due to improved mixing and lower local flame temperatures as the firing rate (and therefore the air flowrate) goes up. Similar behavior is seen as the excess air level increases, which leads to more air flow for the same amount of fuel combusted and therefore better mixing and lower flame temperatures due to dilution. Figure 9 also shows that NOx levels increase slightly as H_2 is added to the natural gas fuel. This is because of the higher flame temperature of H_2 which increases NOx formation in the flame. At all 3 burner firing rates and fuel blends the NOx emissions can be pushed down to the 5 to 15 ppm level through the use of excess air. More development work in this area should allow NOx rates to be reduced even further. This is not an issue with direct air heating applications, but could impact efficiencies in other applications.

A common concern in the pursuit of extremely low NOx emissions is the creation and emission of CO in unacceptable quantities. Figure 10 provides data on CO emissions in the furnace exhaust at the same firing conditions as in Figure 9. These plots show that the burner provides extremely low CO emissions at all firing rates and over a wide range of excess O_2 levels. In almost all cases the CO levels in the exhaust are below 5 ppm (corrected to 3% excess O_2) and in many cases they are below 1 ppm. This shows that the burner provides rapid mixing and fast CO burnout within a short distance. This is specifically beneficial for direct air heating applications. The trends in CO emissions with increasing H_2 blending or firing rate are not as clear as the trends NOx. One reason could be the very low levels of CO under all test conditions. But the addition of H_2 does not have a significant negative impact on CO emissions and should not be a concern in further development of burners for H_2/natural gas blended fuels.

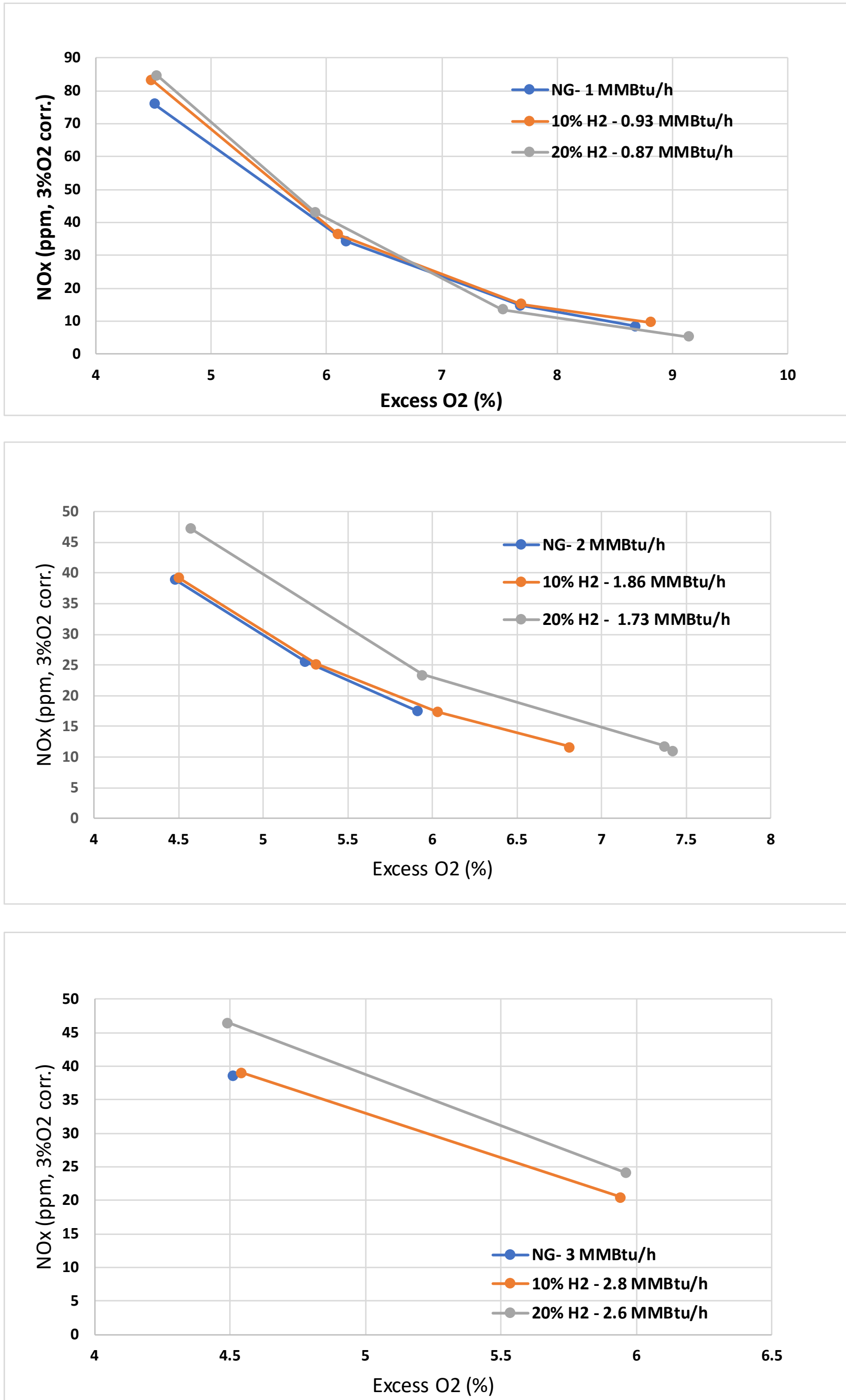

Figure 9. NOx concentration at the furnace exit at different firing rates and excess O_2 levels for 3 fuel blends. For 10 and 20% H_2 blending, the firing rate was de-rated.

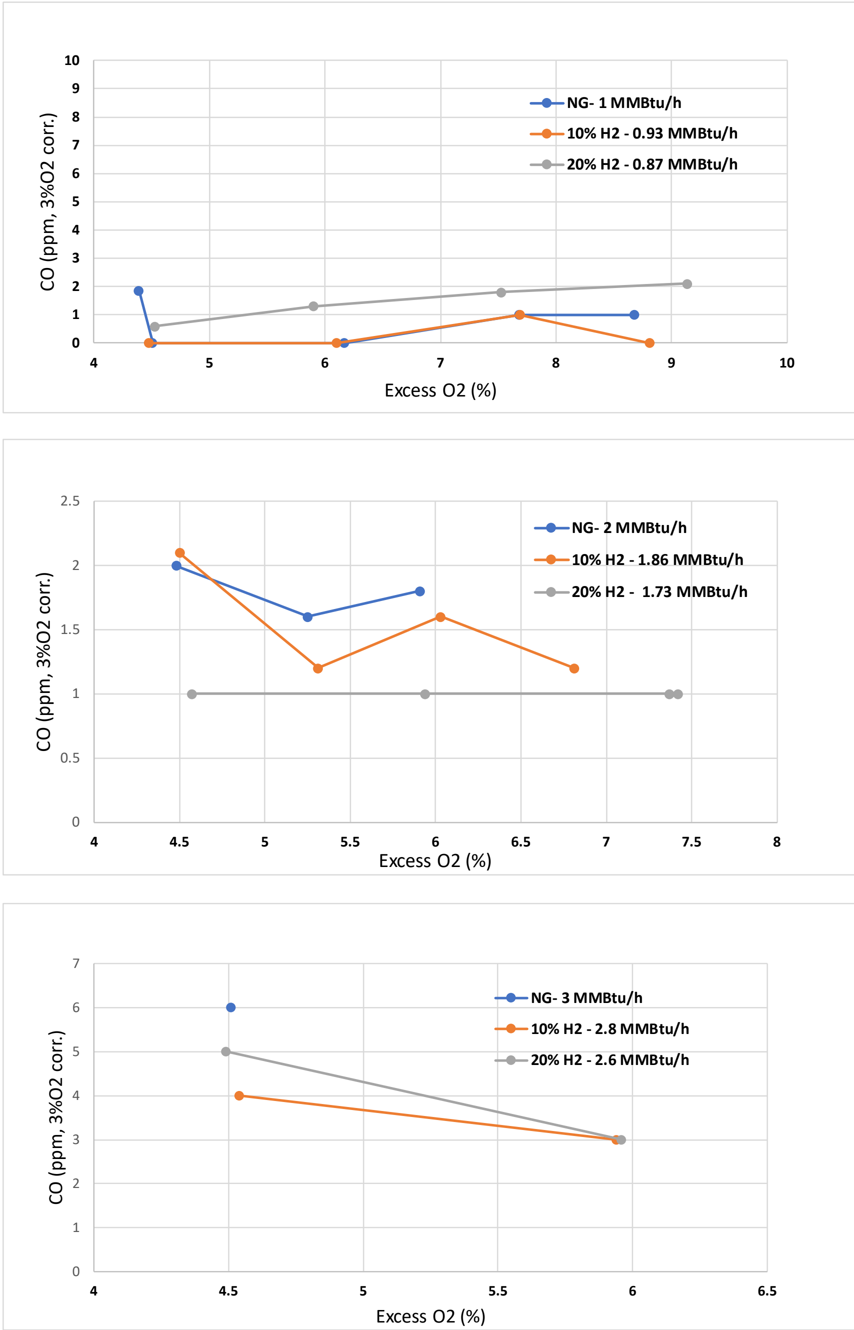

Figure 10. CO concentration at the furnace exit at different firing rates and excess O_2 levels for 3 fuel blends. For 10 and 20% H_2 blending, the firing rate was de-rated

Figure 11 compares flames with natural gas only and natural gas blended with **H_2**. It shows uniformity of the flame fronts with no visible hot spots which suggests stable and robust flame ensuring reliability and durability of the process and the product.

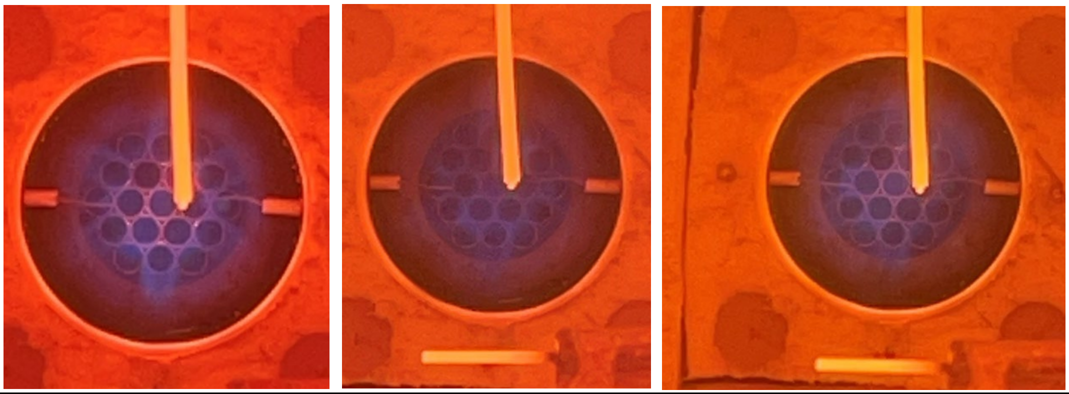

Figure 11. Pictures of flames at 1 MMBtu/h for natural gas only (left), and de-rated for natural gas-10% H_2 by volume (center) and natural gas-20% H_2 by volume (right)

CONCLUSIONS AND RECOMMENDATIONS

GTI has developed a new industrial burner technology for natural gas and H_2 blends, suitable for direct and indirect air heating across various industries. A 3 MMBtu/h prototype was tested at different firing rates and H_2 blend levels (0%, 10%, and 20%) in a lab environment using a process air heating setup. Results show the 3D printed multi-venturi burner would meet many key performance indicators:

- 6:1 turndown for direct or heat exchanger air heating
- Below 10 ppm CO emissions across all conditions
- Robust ignition and stable flames
- Below 40 ppm NOx levels at all firing rates and blends

While the burner meets standard market requirements, aiming for NOx emissions of ≤9 ppm and field testing is recommended for real-world feedback. Further refinements based on this feedback could enhance its attractiveness to manufacturers and users. It is suggested to pursue field demonstrations for both direct and indirect air heating applications.