Design and Development of Advanced 3-D Printed Burner for Process Heating Applications

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

American Flame Research Committee, September 25-27, 2023
Denver, CO

ABSTRACT

GTI Energy (GTI) designed, developed and tested an industrial scale burner technology using 3D printing suitable for both direct and indirect air heating applications for a variety of industries. Two nominal 3 MMBtu/h industrial scale laboratory prototype burners were tested with cross air flow for direct air heating and without cross air flow for indirect air heating. The technology offers potential for significant improvements in natural gas fired air heating, well positioning it against current technologies. The lab prototype burners allowed operation with > 6:1 turndown for heating process air directly or through a heat exchanger. It provided very low CO emissions of below 10 ppm over the entire range of firing rates, which is a challenge for air preheating applications. The burners provided robust ignition and stable flames and burner design II provided superior NOx performance with below 25 ppm NOx at 6% excess O2. Incorporating further refinements based on feedback from the host site and field testing should make the technology more attractive to both the Original Equipment Manufacturers (OEM's) and end users.

INTRODUCTION

Process air heating is a significant market with applications include drying, curing, melting, cutting, baking, heat shrinking, de-soldering, metallization, heat staking, sterilization, air scrubbing, laminating, adhesive activation, hot air curtains and air knives. The technology is also applicable to various other industries such as packages boiler burners for paper and pulp industry, food and beverage industry and chemicals and refining industries. Of these GTI is targeting three primary markets for this technology: process air heaters used in automotive and environmental applications, food drying applications and automotive shops requiring indirect heat. Two approaches are used for air heating depending on the application, a) direct-fired air heating, where the combustion products from the burner are typically mixed with relatively large amounts of process air to form a hot vitiated air mixture, and b) indirect air heating where process air is heated by burner combustion products in a metal shell-and tube type heat exchanger. Direct air heating is thermally more efficient, but the resulting vitiated air is not suitable for all applications. For the current commercial burners:

- Typical fuel consumption is 19 -28.8 TBtu/year (assuming 3 MMBtu/h rated capacity operating at 20% of peak output for 8000 hours per year).
- Operating costs are higher than capital costs due to poor operating efficiency.

---

[1] salavandi@gti.energy

- The majority have corrected NOx emissions of 50 ppm but CO as high as 250 ppm still remains especially for direct air heating
- Turndown is accomplished by high excess air additions that lower available heat as the burner transitions to low fire. With this approach, oversizing burners or providing rapid heating in ovens results in normal operations at higher excess air levels.

The GTI technology aims at filling a key gap of reducing supply chain logistics, poor environmental performance, and low energy efficiency. A novel, scalable, low emissions, high efficiency packaged burner system for air heating may greatly improve customer choices for all end-use applications.

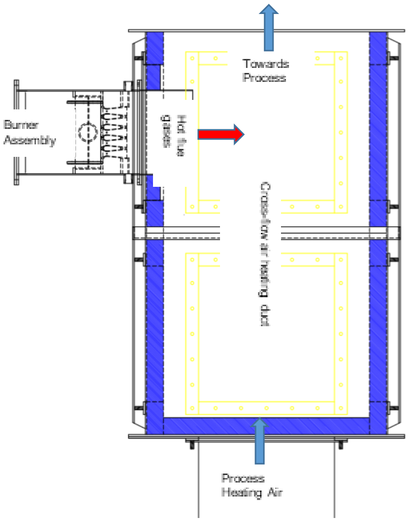

Figure 1: Schematic of complete assembly with burner and cross air flow duct

Figure 1 shows a schematic of the burner and an internally insulated cross air mixing chamber. The burner uses multiple nozzles to improve air-gas mixing and cross-sectional air-gas distribution. The commercial success of the design is based on the lowest possible cost to manufacture. For the burner design it was important to avoid castings and use advanced and precision manufacturing, hence 3D printing was an attractive manufacturing alternative.

Two different manufacturing techniques were evaluated for fabricating the nozzle assembly for the burner. (1) Precision manufacturing: The individual test nozzles were machined using Swiss type lathe and the production cost, in volume, was low enough to produce a commercially viable product. This approach allowed fine tuning the geometry without modifications to expensive tooling. Experiments were conducted using an internal tool with a clamping device only to determine what expansion is possible without material tearing. After each nozzle was fabricated, high temperature brazing for the burner assembly was determined to be the most cost effective with CNC controlled TIG welding best for high temperature operation. (2) 3D printing: 3D printing of the complete burner nozzle assembly as a single step operation can reduce the labor and tooling costs. In addition, there is no need to braze the different nozzles together for further assembly, hence was chosen as a preferred approach.

LABORATORY TESTING

Two burner designs were tested. - Design I for both direct and indirect fired air heating and Design II with longer nozzles to enhance mixing for indirect fired air heating only. Table 1 lists the key measurements made during these tests and the respective instruments used. A Nafion dryer was used to dry the sample prior to entering the emissions monitors. The results presented for emissions in this report are therefore on a dry basis.

Table 1. Measurements and instruments

	Key Measurement	Instrument
1	O2, CO, CO2 and NOx	Water cooled sampling probe, membrane sample dryer and continuous emissions monitors
2	Combustion chamber temperatures	Thermocouples
3	Combustion air flow rate	Mass flow meter
4	Cross air flow rate	Mass flow meter
5	Natural gas flow rate	Mass flow meter
6	Furnace pressure	Magnahelic pressure gauge
7	Temperatures and pressures	Thermocouples and pressure transducers

Test Setup for Direct Air Heating

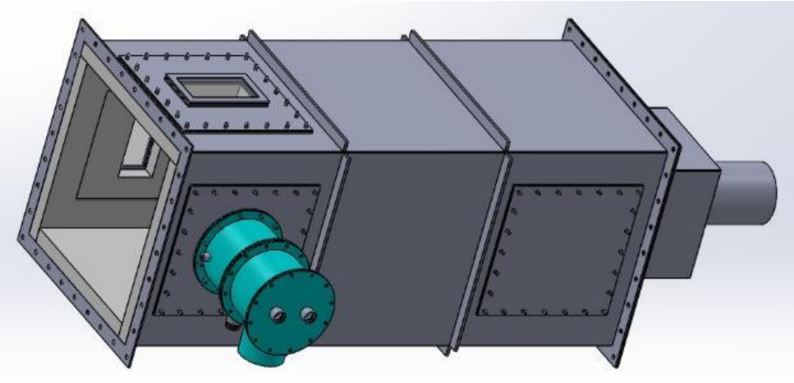

Figure 2: Design I burner and cross air flow mixing chamber

For direct air heating applications, the burner was fired into a stream of cross air. Figure 2 illustrates the design of this arrangement. The cross air mixing duct is made from sheet steel in three sections. The duct is insulated on the inside with ceramic blanket. The burner was installed in the sidewall of the section that connects to the test furnace, while cross air flow was supplied at the opposite end of the duct. The extra length upstream of the burner was provided to flatten the cross air flow profile at the burner and improve mixing of the combustion products from the burner with the cross air stream. Note, the third section of the burner is not visible as it was inside the duct.

Figure 3 shows the left and the right side views of the test system during Design I burner evaluation. As discussed earlier, only the Design I burner was tested with this setup. During some of the earlier tests, a gas sampling probe was installed in the duct (Figure 3 center) to measure concentrations of O2, CO, CO2 and NOx. These, combined with similar measurements made at the furnace exit, were used to confirm the accuracy of natural gas and air flow measurements. Figure 3 right) shows the left side view of the test furnace. The water cooled probe can be seen at the back end of the furnace and the sample dryer can be seen along the side of the furnace near the bottom of the front to middle furnace sight ports. These are the tall and relatively narrow ports visible in the side wall. The ports are equipped with high temperature glass to allow a clear view of the furnace interior.

Figure 3: Design I burner (left) and cross air flow mixing chamber installed on the GTI test furnace (left, center) and Sideview of test furnace with emissions sampling probe installed at the far end (right)

Test Setup for Indirect Air Heating

For indirect air heating applications, the burner was mounted directly on the furnace as shown in Figure 4. A flange adaptor was designed and fabricated to facilitate installation. As with the previous duct installation, the front section of the burner is on the other side of the flange and is placed inside the furnace. Both Design I and Design II burners were tested using this test arrangement.

Figure 4: Setup for tests without cross air flow firing directly inside the furnace

3D PRINTED BURNER DESIGNS

Burner Design I

Figure 5 shows the nozzle assembly that was manufactured using 3D printing. The two plates visible in the left photo form the natural gas plenum when fully assembled into the burner housing. Natural gas is supplied to the plenum into the nozzles and mixed with the combustion air flowing through the nozzles.

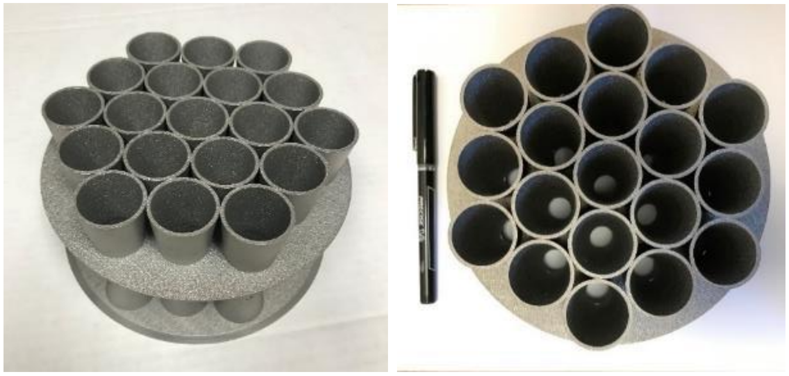

Figure 5: As-received Design I nozzle assembly

Figure 6 shows drawings of the Design I burner housing incorporating the nozzle assembly. The larger inlet at the top is for combustion air and the smaller inlet is for natural gas. The other openings in the housing are for ignition, instruments and flame sighting.

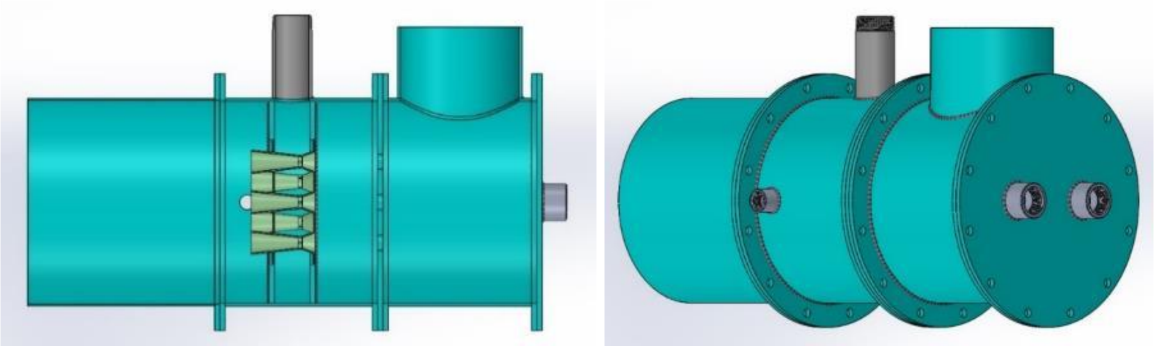

Figure 6: Drawings of the Design I burner

Burner Design II

Figure 7 shows the nozzle assembly for burner Design II. The key difference from Design I is the length of the nozzles. The Design II nozzles had an extended mixing length with all other parameters similar to the Design I nozzles.

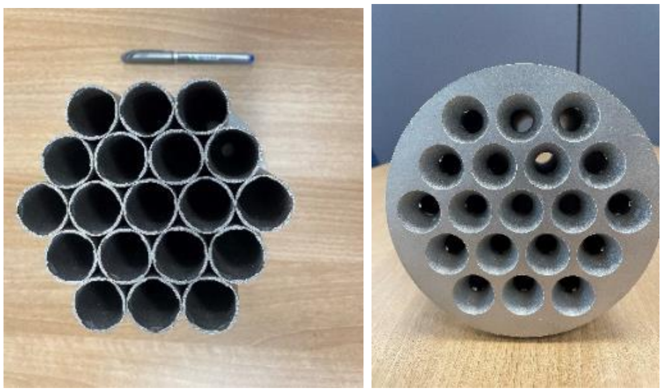

Figure 7: As received design II nozzle assembly

Figure 8 shows drawings of the Design II burner housing incorporating the nozzle assembly. As with the Design I burner, the larger inlet on the side is for combustion air and the smaller inlet is for natural gas. The other openings in the housing are for ignition, flame sensor and other flame safety instruments. Figure 9 shows the middle section of the fabricated burner that houses the nozzle assembly. The coupling on the right of the left photo is for the flames sensor. A similar coupling on the opposite side is for the ignitor.

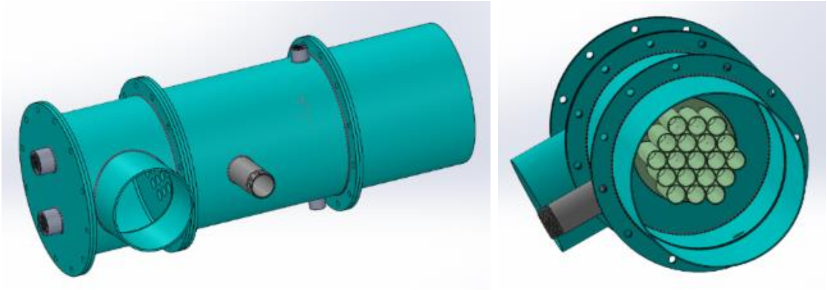

Figure 8: Drawings of the Design II burner

Figure 9: Sideview and combustion air inlet ends of the fabricated Design II burner section housing the nozzle assembly

RESULTS AND DISCUSSIONS

This section presents the results of testing carried out with the Design I burner in both direct and indirect fired arrangements and the Design II burner in indirect fired arrangement. The reasons for this were 1) the testing of both designs for indirect firing provided a good comparison of their combustion and emissions performance, 2) the front of both burner designs, downstream of the nozzles are similar, so similar impacts of cross air mixing are expected on both designs.

The results show the burners met many of the Key Performance Indicators that were set:

- Stable ignition and combustion characteristics – *both Design I and II burners performed well in terms of ease of ignition and stable combustion over their test ranges of 6:1 turndown from 0.5 to 3 MMBtu/h*
- NOx emissions <9 ppm and CO emissions <10 ppm (@3% corr. O2) – *for both Design I and II burners, while CO remained below 10 ppm at nearly all test conditions, NOx was in the 10 to 35 ppm range at the target excess O2 levels of 6 to 9% for the Design II burner. The Design I burner required higher excess O2 levels to achieve similar NOx levels.*
- High turndown (6:1) – *Design I achieved a 6:1 turndown, while the Design II burner was only tested over a 4:1 turndown.*
- Stable, robust operation in cross air flow – *Achieved with the Design I burner. Temperature of the preheated air from 400 F to 1600 F was achieved. Design II burner was not tested with cross air flow. Because both burners are identical*

downstream of the nozzle exits and both performed well without cross air flow, it is expected that the Design II burner should work well with cross air flow.

Figure 10 compares the appearance of the flames from the Design I burner at firing rates of 0.5, 1, 1.5, 2, 2.5 and 3 MMBtu/h (clockwise starting from top left). The pipe shown on the left is the water cooled sampling probe. As seen, the flames in all cases are blue but appear to be cloudier as the firing rate increases. This could be caused by an increase in flame length from the individual nozzles and their merging. The photographs were taken from the port across the burner in the cross air duct. Similar photographs could not be taken for the Design II burner, as it was installed directly on the furnace.

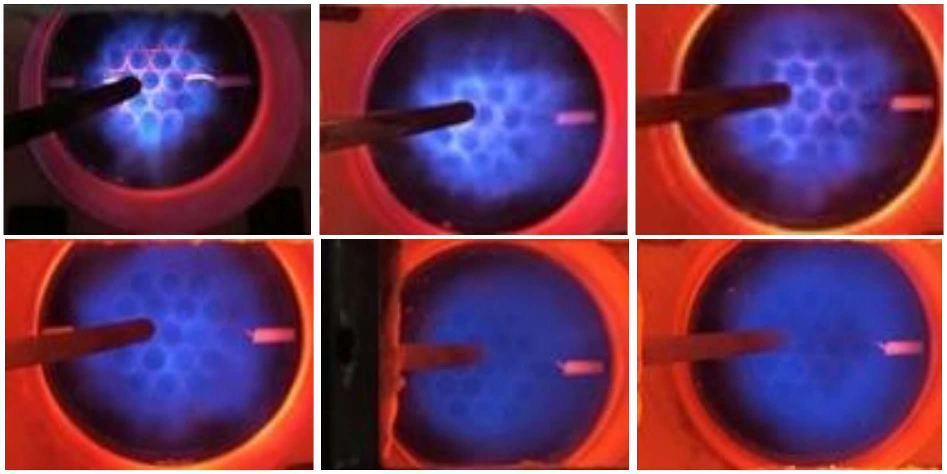

Figure 10: Design 1 burner flames at increasing firing rates (clockwise from top left)

Figure 11 shows the NOx concentration at the furnace exit at different firing rates and excess O2 levels for the Design I burner. As is common with premixed type natural gas burners, at all firing rates, NOx decreased with increasing excess O2 concentration because of decreasing flame temperature. One exception was the lowest firing rate, where NOx first increased as the excess O2 increased to 6%, and then decreased with further increases in excess O2. One possibility is that at the lowest firing rate, the level of combustion air-natural gas mixing was weak due to low combustion air and natural gas flow rates and velocities, especially at the lower excess air levels. The lower mixing levels at low firing rates is also consistent with the associated generally higher NOx levels.

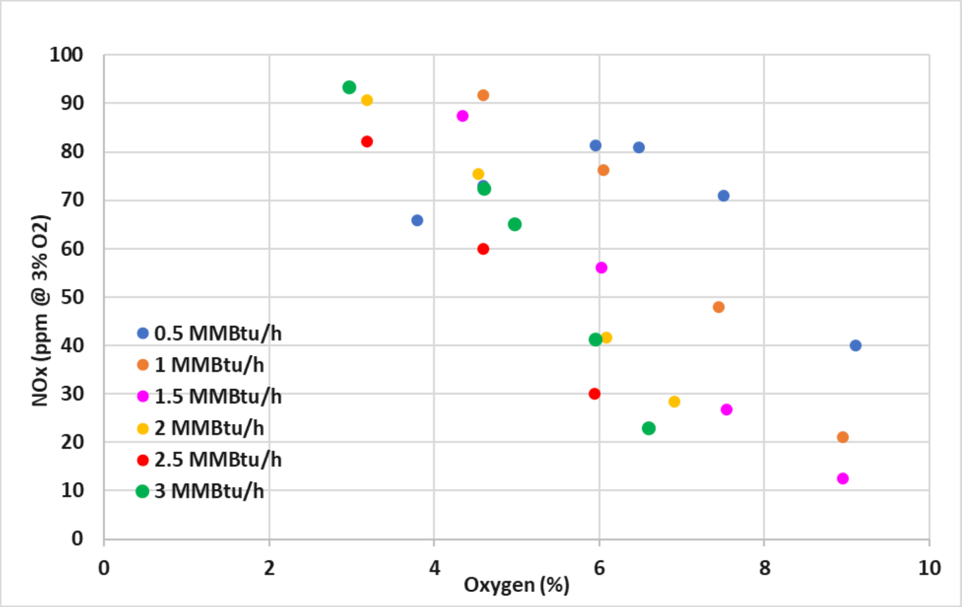

Figure 11: Design I burner NOx concentration at the furnace exit at different firing rates and

Figure 12 presents NOx at the furnace exit as a function of excess O2 for the two burners designs. The excess O2 levels here are a better measure of the excess O2 level at the burner. The results are consistent with the previous charts in that NOx decreases with increasing excess O2 level and firing rate. The NOx values are lower for the Design II burner, with the differences generally more pronounced at higher excess O2 levels and lower firing rates.

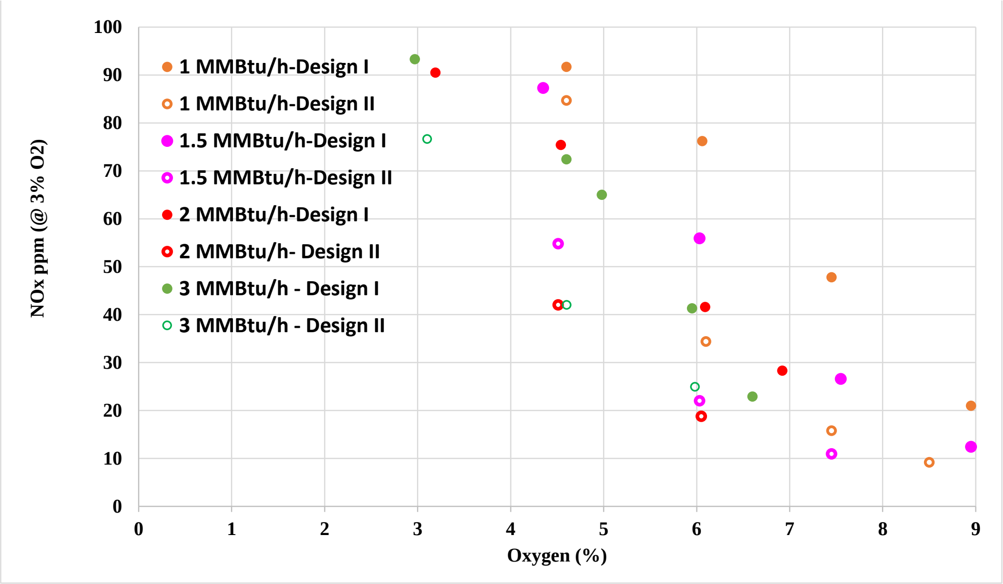

Figure 12: NOx at the furnace exit as a function of the excess O2 at different firing rates for Design I and II burners

Figure 13 focuses on ≤40 ppm NOx, which is a market advantage for these type of burners. It is a zoomed in view of the data from Figure 12. While the Design II burner was able to achieve these NOx levels at all firing rates tested with ~6% excess O2, the Design I burner required higher excess O2 levels.

Figure 14 shows CO at the furnace exit as a function of excess O2 for the two burners following damper improvements to reduce air infiltration. CO emissions were ≤5 ppm, except at maximum firing rate of 3 MMBtu/h with the Design II burner, where the CO was about 8 ppm when the excess O2 was reduced to ~3%.

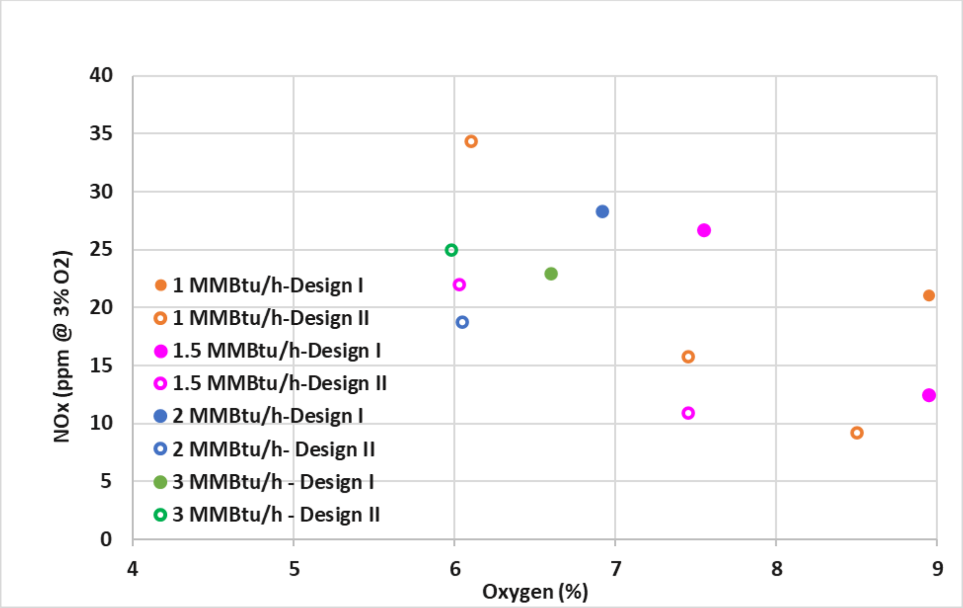

Figure 13: NOx at the furnace exit for high excess O2 levels at different firing rates for Design I and II burners

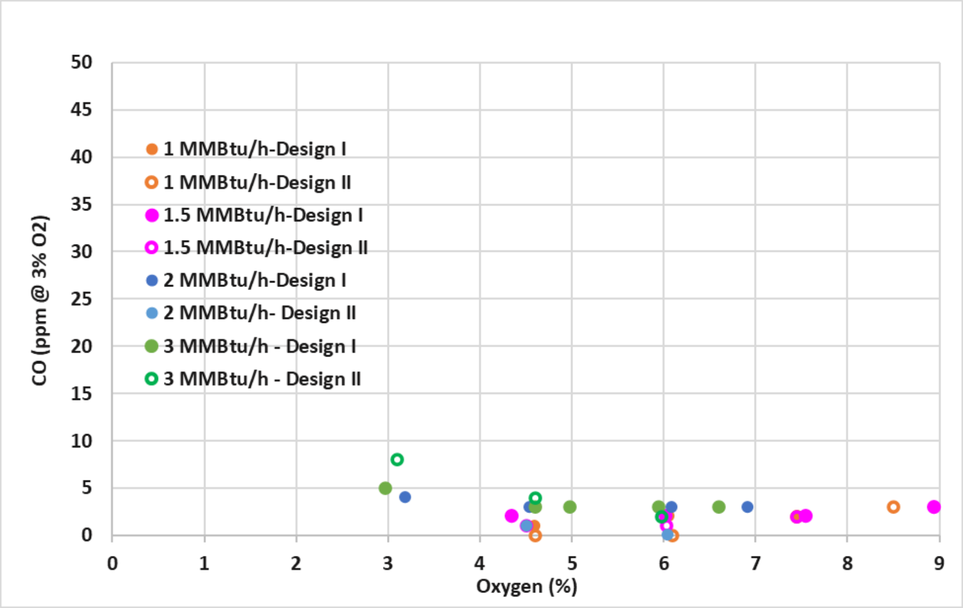

Figure 14: CO at the furnace exit as a function of the excess O2 at different firing rates for Design I and II burners

CONCLUSIONS AND RECOMMENDATIONS

GTI has developed a new industrial burner technology using 3D printing for both direct and indirect air heating applications in a variety of industries, including automotive and food drying. Two nominal 3 MMBtu/h laboratory prototype burners were tested with cross air mixing for direct air heating and without cross air for indirect air heating. Detailed tests and measurements carried out at GTI on an industrial scale furnace that demonstrated the key performance characteristics of these burners. Based on the results, it can be concluded that the 3D printed multi-nozzle burner approaches tested met many of the key performance indicators that were set. The technology offers potential for significant improvements in natural gas fired air heating, positioning it well for current market conditions. The lab prototype burners:

- Allowed operation of > 6:1 turndown to heat process air directly or through a heat exchanger
- Provided very low CO emissions of below 10 ppm over the entire range of firing rates
- Provided robust ignition and stable flames
- Burner design II provided superior NOx performance with below 10 ppm NOx (market advantage for these type of burners)

The key performance characteristics of the burners, e.g. combustion air pressure requirements, turndown capability, ease of ignition, flame stability, and CO and NOx emissions are expected to meet standard market requirements. However, as a new technology, it would be preferable to achieve NOx emissions of ≤9 ppm over a turndown of 6:1, which GTI is working towards. The technology should also be tested in a field environment for real world feedback. Incorporating further refinements based on this feedback should make the technology attractive to both the equipment manufacturers and end users. It is recommended to pursue demonstration of this technology in a field setting, preferable for both direct and indirect air heating.