The World's First Flameless Crude Heater

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ABSTRACT

By June of 2014, the world's first flameless refinery heater located in Coffeyville, Kansas will have been operating in the flameless mode for over one year. At the A&WMA annual conference in June, Great Southern Flameless (GSF) will proudly present over one year's worth of actual operating and performance data along with photos and video from this first flameless crude heater operation.

Based on a Consent Decree with the US Environmental Protection Agency (EPA), Coffeyville Resources purchased the flameless crude heater for their Coffeyville, KS refinery. This is a demonstration heater to prove that flameless technology is commercially viable for achieving selective catalytic reduction (SCR) level nitrous oxide (NO_x) emissions in the refining industry. The timeline for the project began on January 23rd, 2012 with the first flameless heater purchase order and the heater was shipped at the beginning of October, 2012. Installation, instrumentation and controls ran a bit over the planned schedule with commissioning/start-up commencing in late February, 2013, and the first flameless firing documented on April 22, 2013.

While high temperature air combustion (HTAC) and flameless combustion are not at all new concepts, they are both new to the direct fired process heater industry. GSF's flameless crude heater can be run both conventionally and in flameless mode with a predicted 3-8 ppmvd NO_x without a selective catalytic reduction (SCR) process. The flameless combustion heater will meet the process radiant flux requirements, increase efficiency and reduce emissions during normal operations.

GSF has developed this revolutionary flameless technology which utilizes HTAC for maximum efficiency (91% lower heating value (LHV)) and carbon dioxide (CO_2) reduction yet the flameless combustion process produces NO_x levels which have previously only been achievable with an SCR. The cost of this system is equivalent to a conventional double fired heater with a conventional balanced draft air preheat system.

Great Southern Flameless combustion technology has now been commercially proven in a refinery environment and is approved by the EPA for consent decree NO_x compliance. With the flexibility of being able to seamlessly transition back and forth between flameless and conventional combustion, there is zero risk to meeting production goals and process heat requirement.

INTRODUCTION

Flameless combustion has been incorporated into both the glass and steel industry furnaces for many years. Both of these applications operate at extremely high temperatures and run at constant steady state conditions. These are ideal conditions for sustaining flameless combustion. Flameless combustion had never been introduced to the refining industry due to the day to day variance in operation and cooler temperatures of refinery process heaters. GSF has developed a flameless furnace technology[1] which accommodates all the required operation variances in a refinery heater and still provides NO_x emissions similar to that of an SCR.

The goal for this project was to prove that flameless combustion heaters could be successfully integrated into the refining industry and still provide SCR level NO_x emissions. On April 22, 2013 the technology was proven and the first flameless fired crude heater was in operation.

Commercialization of the technology required GSF to address numerous design features to have a flameless heater operating in the refining environment. Because the heater does not incorporate burners in the traditional sense of the word, Great Southern coined the term "Flameless Nozzle Grouping", or FNG, to describe the fuel and air nozzle assembly. Included with the FNG fuel delivery system is a patent pending 3-way ball valve designed by GSF specifically for the flameless heater application.

Because refinery heaters do not always run in steady state, the flameless heater must be able to accommodate swings in firing rate. Therefore GSF also designed a convection section bypass system with automated dampers in order to accommodate the changes in process and turndown firing rates.

While this demonstration heater is relatively small, GSF has already designed the flameless heater for much larger applications to accommodate all ranges of required process duty. The symmetry of the furnace lends itself perfectly to scale up for larger process requirements.

Safety is of the utmost concern in refinery operations and GSF has also designed the flameless monitoring system and required control logic for the burner management system (BMS). The heater operates just as any typical balanced draft heater system. Only a few added safety systems are required for flameless combustion and these have been designed to operate automatically so that operators are not required to learn any new procedures.

This paper provides a more detailed overview of the equipment design, a description of how and why the flameless heater works as well as performance results and photos from the field. Also included is a discussion about the safety control system for the heater and why the flameless heater is the safest system available.

DESCRIPTION OF THE APPLICATION SPECIFICATIONS

The Coffeyville refinery processes a mid-weight crude oil. Currently, there are two other crude heaters that operate in parallel with the flameless demonstration heater. The process specifications for the demonstration crude heater design were as follows:

Total Absorbed Duty: 9.5 MMBtu/hr
Process Flow Rate: 3,442 BPD
Process Inlet Temp: 385 ^{o}F
Process Inlet Pressure: 137 psig

Process Outlet Temp: 705 ^{o}F
Process Outlet Pressure: 35 psig
Draft: Balanced Draft System
Combustion Air Temp: 873 ^{o}F
Fuel: Refinery Fuel Gas, 904-1000 Btu/scf, lower heating value (LHV)
Fired Duty: 10.4 MMBtu/hr (LHV) with preheated air
Excess Air: 15%
Stack Temperature: 300^{o}F
Efficiency: 91.0% (LHV)

While there was not a required guarantee for NO_x emissions, the expectation was to have NO_x levels between 4 and 8 ppmvd while firing in flameless mode.

The control system was to have a safety integrated level of 2 (SIL 2) rating.

DESCRIPTION OF THE EQUIPMENT

As shown on the plan view in Figure 1, this heater required two FNG's in order to meet the process specifications for the necessary heat input. The heater is a polygon with the double fired process coil in the center and (1) FNG on each long wall which fire tangentially around the inside heater walls.

In order to pin the flue gas in circulation against the wall, Great Southern developed and patented a dimple pattern in the castable refractory which holds the flue gas to the wall in a manner similar to the aerodynamics of a dimpled golf ball. Flue gas is allowed to circulate in high volume and velocity around the heater until it eventually migrates out of rotation into the center of the heater, then up and out through the uptake ducts and into the convection section.

To address ease of operability in the transition between conventional, staged and flameless firing modes, Great Southern developed and has a Patent Pending on an automated 3-way switching valve. This valve while in position 1 (conventional firing mode) allows all fuel gas to flow through just the (2) conventional nozzles. In position 2 the valve allows the fuel gas to split where half the fuel goes to the 2 conventional nozzles and the other half of the fuel goes to the (2) flameless nozzles. This is the position which required development and customization for the Great Southern flameless heater application. A standard 3-way, full port, plug valve would have doubled the fuel flow at constant upstream pressure while in position 2. It was necessary for Great Southern to design a plug for this valve so that when firing in position 2 (staged firing mode), fuel gas would flow equally to all (4) nozzles but the upstream pressure, total fuel flow and fuel control valve would remain unchanged for all (3) positions. In position 3 (flameless firing mode) all of the fuel gas is diverted to the flameless nozzles.

The balanced draft air-preheat system, as shown in Figure 2, generates high temperature combustion air. This is required for staged or flameless firing so that the localized "blend" temperature in the radiant section stays above the auto-ignition temperature as required for oxidation of the fuel gas. In order to accommodate flexibility in heater loads/firing rates and to allow for extremely cold ambient air temperatures, the flameless heater is equipped with a convection section by-pass duct and associated dampers so that hot flue gas directly above the radiant section can be blended with the flue gas from above the convection section in order to maintain a flue gas temperature going into the air-preheater which is adequate for heating of the combustion air. In addition, a steam/air heater was designed by GSF to maintain 60^{o}F inlet air temperature to the forced draft (FD) fan and air preheater during cold ambient conditions. Beginning with the process heater design, the radiant section is comprised of a single pass, double fired coil. Tube spacing is critical for optimum efficiency and heat flux.

Three key features which generate the higher than normal radiant efficiency of this heater are: 1) The interior walls are lined with castable refractory inlayed with a proprietary dimple pattern which helps to hold the flue gas in rotation against the interior walls and provides additional surface area and view angles for equalized radiant flux to the process tubes. This feature also eliminates any possibility of flame or hot gas impingement on the tubes. 2) The mass of flue gas in circulation is two to three times the flue gas mass of a typical refinery heater design thus assuring even heating and radiation from the heater walls to the double fired coil. 3) The FNG concept provides the motive force for the increased flue gas circulation. Both air and fuel "push" the flue gas, air and fuel away from the FNG. Also, each FNG "pulls" the flue gas towards the FNG.

Once the flue gas has migrated out of rotation and passes through the uptake ducts, it may all pass through the convection section or if conditions require, a portion of the radiant flue gas may pass through the convection section by-pass duct. The amount of flue gas being by-passed is controlled by the convection section diverter and convection section by-pass dampers. These dampers are controlled automatically based on the combustion air temperature set-point of 850^{o}F. If higher combustion air temperature is required to meet or maintain this set-point then the diverter damper begins to close and the by-pass damper begins to open simultaneously, allowing more hot gas from the radiant section to by-pass the convection section and go straight to the air preheater. This feature allows continuous flameless operation for extended turndown conditions thereby providing the widest possible operating range for flameless operation. The 850^{o}F combustion air temperature is required in order to maintain a "blend" temperature inside the radiant section that is above auto-ignition temperature for the fuel gas. This high temperature combustion air also contributes to the radiant efficiency thereby reducing the size and cost of the convection section. The by-pass duct and the (2) convection section dampers are the only real mechanical difference between the Great Southern flameless heater air-preheat system and any other balanced draft air preheat system.

One FNG is comprised of (2) sets of (2) fuel nozzles each and one set of (4) combustion air nozzles. The fuel and air nozzles are paired such that the heater can run indefinitely in any of the three firing modes, conventional, staged and flameless. The conventional nozzles require just (2) equal size fuel injection ports each and the flameless nozzles use only a single large port on each fuel nozzle. The large fuel ports on all nozzles reduce plugging and therefore reduces field maintenance. The air nozzles required particular design consideration in order to establish the required flow pattern and mixing needed to stabilize the conventional nozzle flames. Traditional burner tiles are no longer needed for stabilizing a conventional flame. In flameless mode, there is no need for any flame stabilization whatsoever as the combustion reaction is occurring throughout the volume of flue gas in rotation with no visible flame burst. The resulting NO_x levels are equivalent to an SCR.

Figure 1. Plan View of Heater

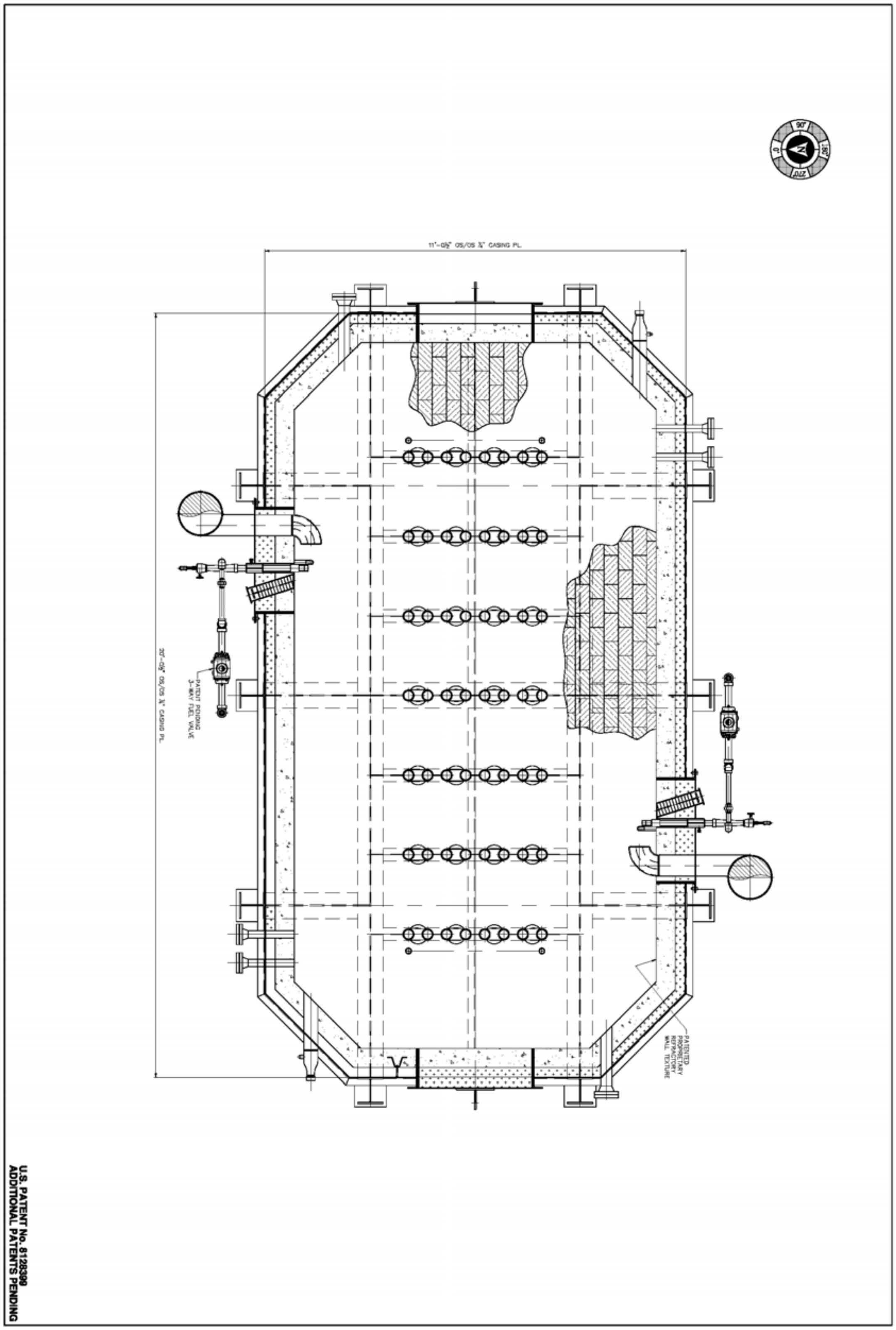
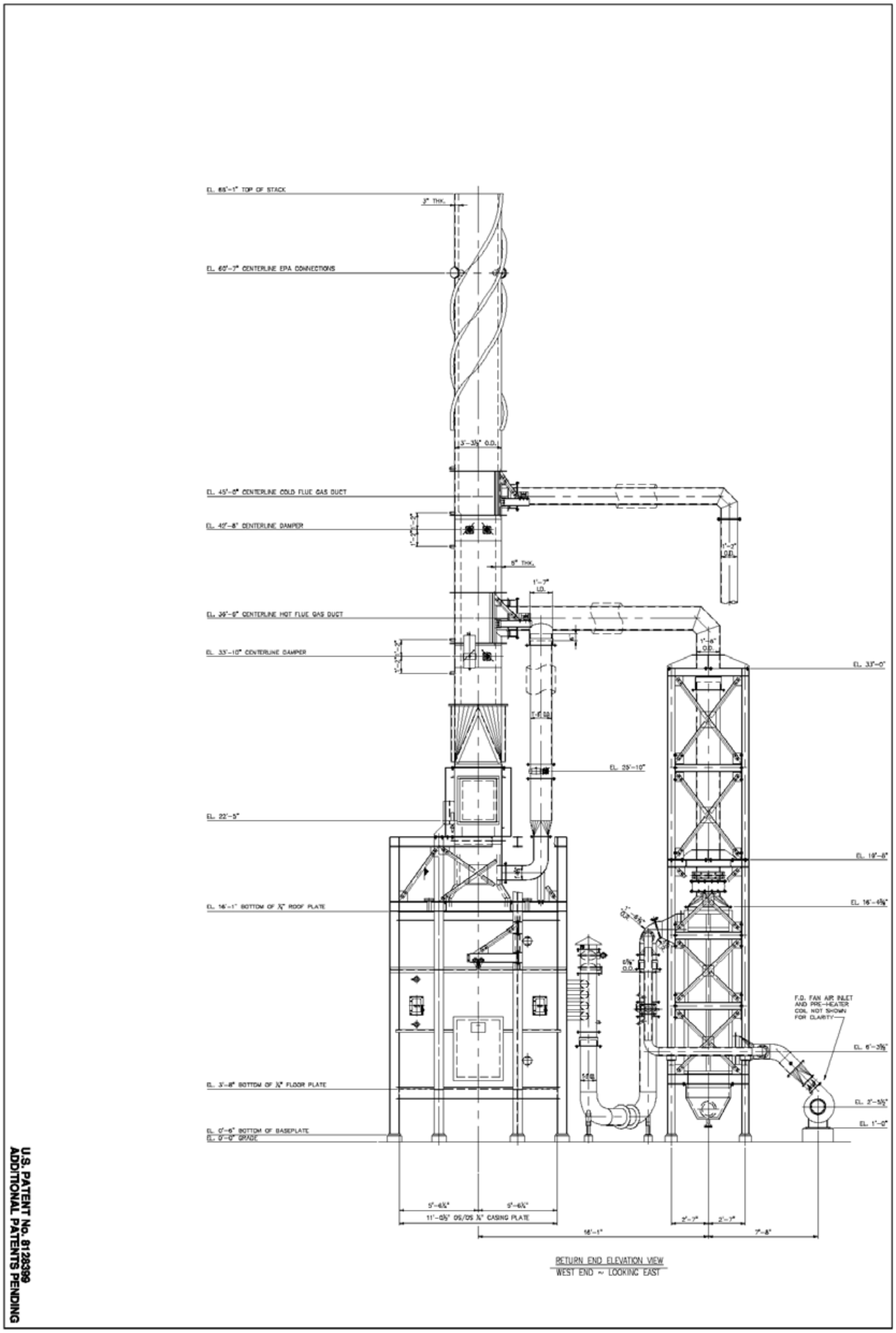


Figure 2. Side Elevation View of Heater

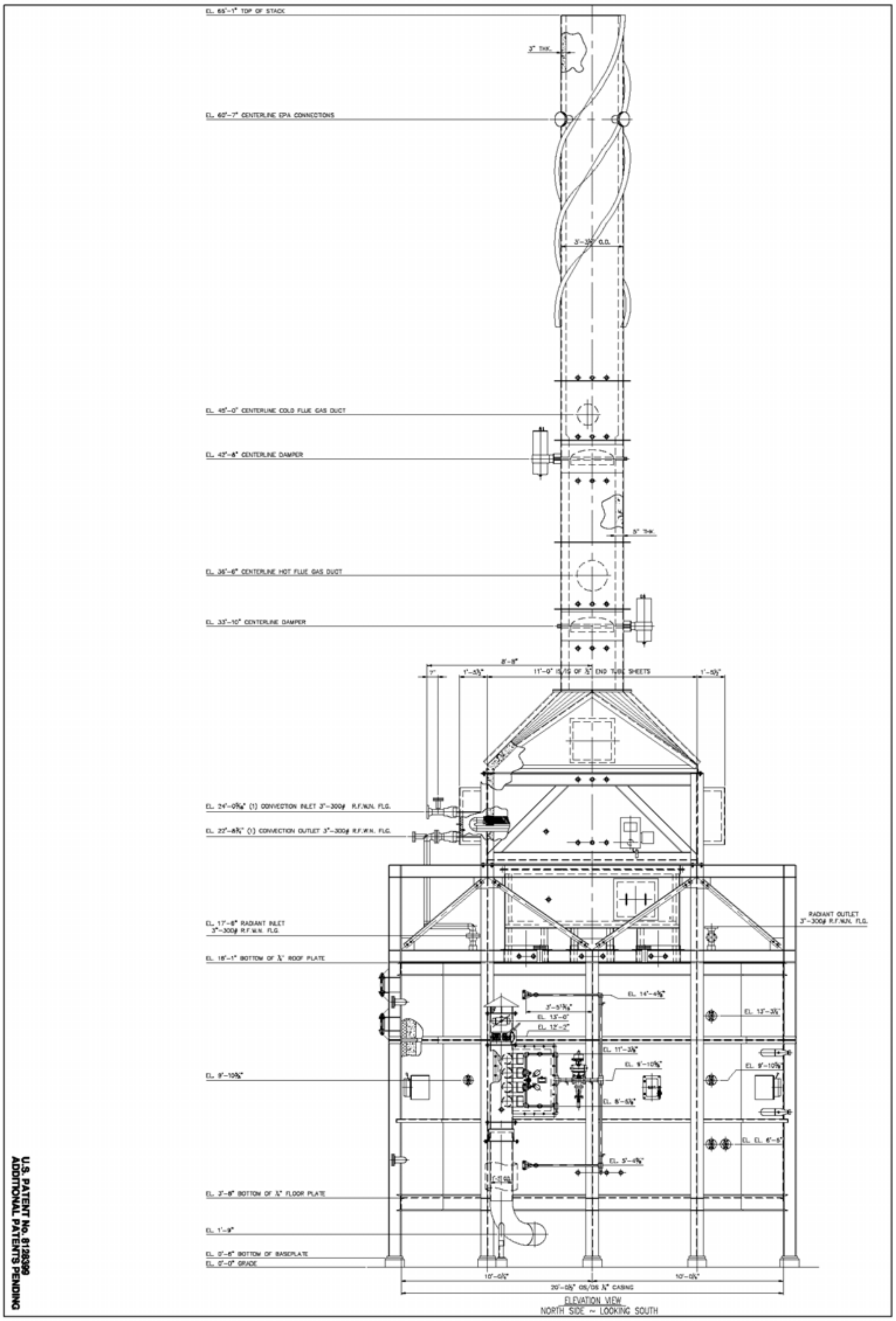


Included with each fuel nozzle/manifold assembly is the 3-way fuel valve. This is a directional valve only and serves to control the mode of firing. A single fuel gas line is connected to the 3-way valve inlet and the 3-way valve directs the fuel flow to one of the (3) firing modes. The valve will very quickly and smoothly transition between all of the firing modes and is equipped with position switches as well as position confirmation feedback. As noted previously, this is a customized valve developed by Great Southern with Patent Pending that will maintain constant fuel flow in each of the (3) firing modes with constant upstream pressure so that the owner's main fuel control valve does not require adjustment when switching between firing modes. The valve controls are tied to the overall heater BMS and will only transition into or remain in either the staged or flameless firing mode if the temperature permissives are continuously met. There will be additional detail on permissives in the controls discussion to follow.

The heater is started up in natural draft, conventional firing mode and is equipped with automated natural draft air doors as are shown in Figure 3. The heater can be run indefinitely in conventional, natural draft mode or in any of the 3 firing modes while on air-preheat. If any event or condition occurs that may trip the fan(s)/air-preheat system, the automated natural draft air doors will open, the stack dampers will open and the 3-way valve will return to position 1, conventional firing. This allows for wide variety and range of continuous operation.

Very few additional instrumented items need to be added to the owner's normal control system for a typical balanced draft air-preheat system. These items include the (2) convection section diverter and by-pass control dampers, the 3-way valve on each FNG and (4) thermocouples per FNG. (3) thermocouples are located downstream of the FNG, mounted at (3) different elevations through the heater wall, which are used to monitor combustion. Another thermocouple is located through the heater wall just upstream of the FNG. This reading is used in the calculation of the "blend" temperature. The "blend" temperature is calculated using the combustion air temperature and the upstream FNG thermocouple value. This "blend" temperature must remain above the programmed auto-ignition set-point in order to transition to or remain in either the staged firing and/or flameless firing modes. The "blend" temperature and the combustion air temperature are both permissives which must be met and maintained to operate in the staged or flameless firing modes.

Figure 3. Elevation View of Heater



HOW IT WORKS

From cold start, the heater is brought up in natural draft mode in the same manner as any typical conventional heater. With the natural draft air doors open, the pilots are lit and then the conventional nozzles are lit one by one off of the pilots. Rates are gradually increased to design duty. The air-preheat system can then be started up in the same manner as any typical balanced draft air-preheat system. The convection section diverter and by-pass dampers can be modulated if needed in order to achieve combustion air temperature of 850^{o}F or greater.

Once the combustion air temperature meets or exceeds the 850^{o}F permissive and the "blend" temperature exceeds the permissive set-point, the heater is ready to transition into staged fuel firing mode. Because of Great Southern's Patent Pending 3-way valve design, the valves can be actuated into staged firing one at a time without impacting the firing rate to any FNG or upsetting the main fuel control valve. The valves automatically actuate one by one with position confirmation on each valve. In staged firing mode, half of the fuel is diverted to the flameless nozzles while the other half of the fuel remains through the conventional nozzles. It is recommended to hold in staged firing for a reasonable period of time until temperatures equalize throughout the heater and steady state operation is achieved.

Along the heater wall there are (3) vertical temperature zones. The zones are upper, middle and lower. In each firing mode the temperatures change with the middle zone decreasing in temperature and the upper and lower zones increasing in temperature. As expected, the (3) zone temperatures are most uniform in the flameless firing mode. A tabulation of the measured zone temperatures for the 3 firing modes is included in Table 1 on the following page.

Provided that all temperature permissives are continuously met, the heater can now be transitioned into flameless firing mode. Once again, the 3-way valves will actuate one by one into position 3 with position confirmation feedback. The fuel is then all diverted to the flameless nozzles. Visible flame from the conventional nozzles disappears and the heater simply begins to glow. The fuel nozzles are located well below and above the air nozzles. The tangentially fired fuel and air nozzles are both entraining inert flue gas that is in rotation and pinned to the wall by the refractory dimple pattern. The fuel and air eventually diffuse into each other and the combustion reaction takes place but without a flame burst. The radiant section temperatures become more uniform throughout the entire heater and because it is above the auto-ignition temperature, the combustion reaction is sustained. The adiabatic flame temperature of a conventionally stabilized, visible flame is upwards of 2700^{o}F and this is why, where and how high level NO_x emissions are formed. In the flameless combustion mode, the oxidation reaction is taking place at temperatures in the range of 1500-1700^{o}F thus reducing NO_x to levels of 4-8ppmvd, similar to the levels achievable using SCR. Basically the pre-mix pilots are generating all of the NO_x.

Three levels of thermocouples downstream of each FNG are constantly monitoring temperatures in the combustion zone. If a pre-programmed downward rate of change in temperature is detected at all three levels, the BMS will transition the 3-way valves back to position 1, conventional firing mode. The continuous pilots re-ignite the conventional nozzles and operation may continue indefinitely in conventional mode. This event is unlikely to ever occur however due to the combustion air temperature and "blend" temperature permissives. As long as auto-ignition temperatures are met inside the heater, the oxidation reaction will occur. If a downward rate of change in temperature occurs in conventional mode, indicating loss of combustion, the BMS will shut down main fuel.

If combustion air temperature drops and/or the "blend" temperature drops below the permissive set-points, the BMS will return the valves to position 1, conventional firing. If the FD fan or ID fan should fail, again the BMS will return the valves to position 1 and the natural draft air doors and main stack dampers will all open sending the heater into conventional fire, natural draft mode.

This is the most versatile, simple and safe heater design available and provides emissions levels that were previously only available with SCR systems.

GREAT SOUTHERN'S FLAMELESS HEATER PERFOMANCE

In Table 1 below, note the radiant furnace temperatures at the (3) levels throughout the heater. Through the progression from conventional to staged and then flameless firing, the temperature profile throughout the heater equalizes and hot flame burst zones are eliminated. It is this cooling and equalization of the combustion zone gases which generates the reduction in NO_x.

Figures 4-7 are photos of actual heater operation in each mode from various view ports in the heater. Figure 8 is a snapshot of the flue gas excess oxygen content and the NOx emissions as measured by an Enerac 2000 portable combustion analyzer.

Table 1. Actual Heater Performance

	Conventional Firing Balanced Draft	**Staged Firing Balanced Draft, APH**	**Flameless Firing Balanced Draft, APH**
Combustion Air Temp, ^oF	804	893	909
Avg Radiant Upper Level Temp, ^oF	1544	1740	1714
Avg Radiant Mid Level Temp, ^oF	2050	1826	1476
Avg Radiant Lower Level Temp, ^oF	1488	1627	1669
Excess O_2, %	3.7	2.6	2.4
NO_x, ppmvd	77	49	4

Basis: Radiant Coil Configuration: Double Fired
Fired Duty: 10.4 MMBtu/hr
Fuel Gas Comp: Typical Refinery Fuel Gas
Excess Air: 15%

Figure 4. Conventional Firing. View from across heater.

Figure 5. Staged Firing. View looking into FNG.

Figure 6. Flameless Firing. View from across heater.

Figure 7. Flameless Firing. View from behind FNG.

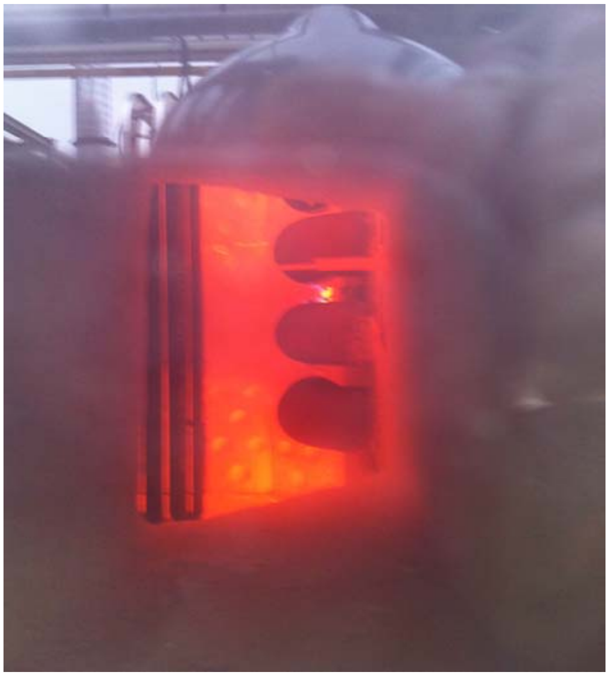
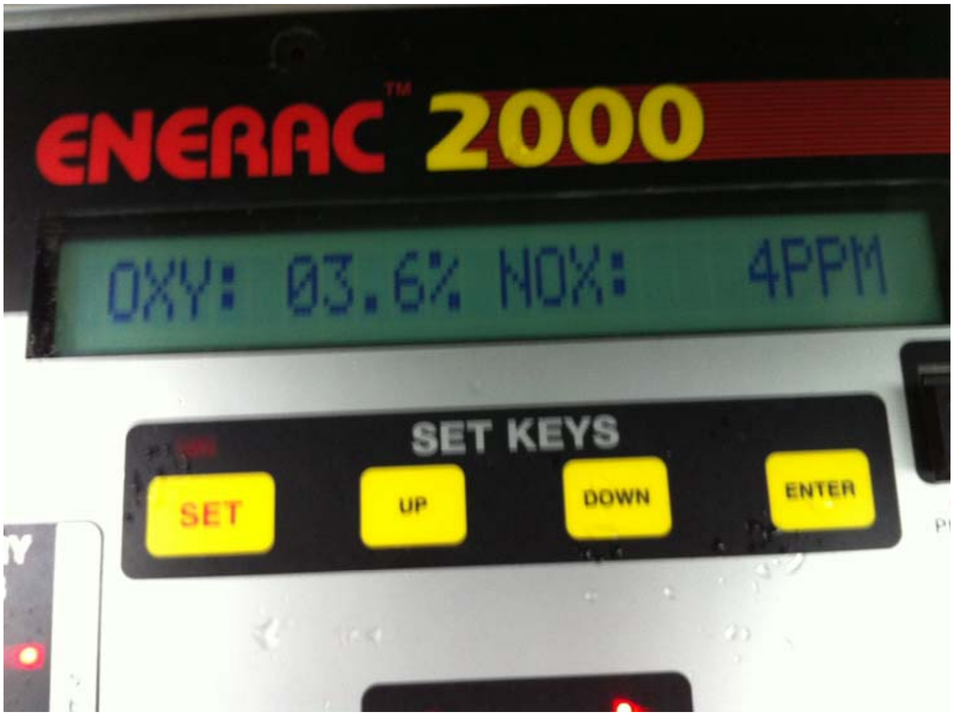


Figure 8. Enerac 2000 Combustion Analyzer. Flameless firing, excess O_2 and NOx.



CONTROLS, MONITORING AND SAFETY CONSIDERATIONS

Because flameless combustion technology is new to the refining and petrochemical industry, the term “flameless” tends to make some people uneasy because it is so different from traditional conventional burners. The fact is that flameless combustion is the safest technology available for transferring heat into the process fluid of fired heaters.

As stated in NFPA 86, 8.10.1[2], for furnace/boiler temperatures over 1400^{o}F, no flame monitoring is required due to conditions well above auto-ignition temperatures. As long as fuel and sufficient air are mixed and local temperatures are above the auto-ignition temperature, the oxidation reaction will occur. In addition, the GSF flameless heater stabilizes the combustion reaction along the heater’s internal refractory wall so there is no burner tile or flame holder that a flame must rely on for stabilization.

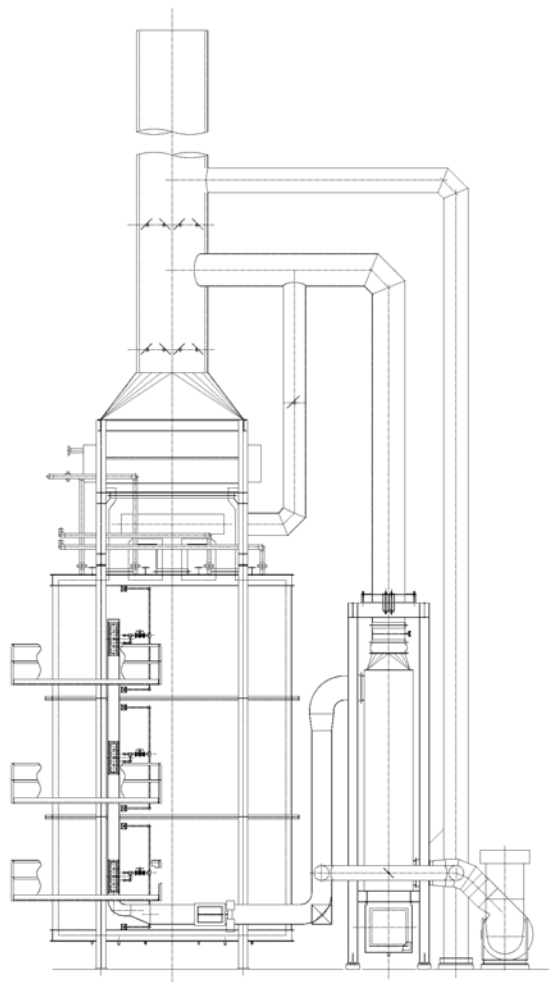
Simple instrumentation and controls that monitor combustion air temperature and recirculating flue gas temperature inside the heater will ensure that auto-ignition temperature requirements are met and maintained whenever the heater is firing in the flameless mode. As long as these temperatures are maintained at or above the set-point, the flame cannot be extinguished or destabilized. If the flue gas or combustion air temperatures should drop below the set point due to loss of a fan for example, the control system would simply switch back to the conventional firing mode on natural draft. With this flexibility the end user can still operate the heater and produce product while a fan or any other external piece of equipment is being serviced.

NEXT GENERATION: LARGE CAPACITY FLAMELESS HEATERS

All Great Southern flameless heaters will incorporate a double fired coil and tangential firing along the wall. The radiant coil can be vertical or horizontal and single or multi-pass. The coil configuration can be in an in-line or cruciform configuration. The inherent beauty of the flameless heater design in general is that it provides dimensional symmetry for both the coil and the FNG's. Symmetrical sections need only be added to length, width and/or height in order to accommodate the required duty for the process and to fit the heater into the available footprint. In reality, the heater will ship as large heater sections, but adding modules to the length and height provides a conceptual example of the ease in maintaining symmetry. The FNG sections will always be positioned to fire in a tangential, head-to-tail manner that will maintain the same proportion of flue gas volume and the same rotational velocity as occurs in the existing demonstration heater presented above.

Figure 9 is an example of how a larger heater may be stacked with (3) levels of symmetrical FNG sections.

Figure 9. General arrangement of vertical tube, double fired flameless cabin heater



ECONOMICS

The capital cost (equipment plus instrumentation and installation) of a Great Southern Conventional Heater with Flameless Firing capability is comparable to a typical conventional, double fired heater with a balanced draft, air pre-heat system. Additionally, savings include fuel energy efficiency, reduced convection section size, reduced maintenance, greater throughput and reduction of the need for emissions credit purchase so there is a measureable return on investment.

SUMMARY

Great Southern Flameless combustion technology has now been commercially proven in a refinery environment and is approved by the EPA for consent decree NO_x compliance. With the flexibility of being able to seamlessly transition back and forth between flameless and conventional combustion, there is ZERO risk to meeting production goals and process heat requirement.

Great Southern's Conventional Heater with Flameless Firing capability also has the flexibility to safely operate with wide ranging fuel compositions.

Furthermore, Great Southern's flameless heater can be retrofit at a later date to utilize 100% oxy-flameless combustion technology to further reduce the size of secondary CO_2 recovery systems that will likely be required in the future.[3]

REFERENCES

1. Gibson, W.C., U.S.Patent 8,128,399, 2012

2. National Fire Protection Association, NFPA 86, Standard for Ovens and Furnaces, 2011 Edition, Section 8.10.1, pp 27.

3. Gibson, William C.; Zimola, Marianne *Oxy-Flameless Combustion Heaters for Refinery Process*, AWMA 2014, June 224-27, 2014. www.GreatSouthernGroup.com