

CFD-Based Design and Field Validation of an Ultra-Low-NO_x Enclosed Flare System for Low-Pressure Waste Gas Applications

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Abstract

Increasingly stringent emissions regulations for flaring systems in refinery, gas production, and oilfield applications are driving the need for advanced combustion solutions. These solutions must achieve ultra-low NO_x while maintaining high destruction efficiency and stable operation across widely varying gas compositions. This work presents the design, computational modeling, and preliminary commissioning results of a retrofit enclosed flare burner developed to meet San Joaquin Valley Air Pollution Control District requirements for NO_x, CO, and VOC emissions. The burner was designed for waste gas flow rates of 250 to 450 MSCFD under very low gas pressure conditions (<0.25 psig), which are known to challenge flame stability, mixing effectiveness, and ultra-low emissions performance in enclosed flare applications.

The flare burner system incorporates a proprietary lobed mixer to enhance fuel-air mixing, a distal flameholder for controlled flame stabilization, and a distributed assist gas injection strategy to enable reliable ignition and stable combustion over a broad operating range, while maintaining minimal assist gas consumption during normal operation. The design was evaluated using steady-state Reynolds-Averaged Navier–Stokes (RANS) CFD simulations with detailed chemical kinetics, modeling waste gas compositions ranging from 710 Btu/SCF to 1150 Btu/SCF (LHV) at firing rates up to 25 MMBtu/h.

CFD results demonstrated uniform temperature distribution and strong flame attachment at the distal flameholder. They also showed complete combustion within the enclosed stack volume without evidence of flame lift-off. Predicted emissions across all simulated operating conditions were below regulatory limits, with NO_x, CO, and VOC levels consistently below 0.009, 0.004, and 0.001 lb/MMBtu, respectively. These results indicated effective mixing and controlled combustion performance across both turndown and maximum firing scenarios.

Preliminary commissioning observations were consistent with CFD predictions, showing reliable pilot-assisted ignition, stable flame anchoring, and controllable operation across varying process conditions. A temperature and O₂-controlled air delivery system utilizing a variable frequency drive (VFD) demonstrated effective regulation of combustion conditions.

Final field measurements confirmed low-emissions operation following commissioning and tuning. The official source test measured NO_x at 10.4 ppm corrected to 3% O₂, corresponding to 0.0126 lb/MMBtu (HHV), while CO and VOC were both reported as zero.

These results validated the implemented flare burner design as a practical and scalable retrofit solution for achieving ultra-low emissions while maintaining operational simplicity and reliability.

1. Introduction

Enclosed flares and incinerators remain essential equipment for managing waste gas streams in oilfield and industrial operations. In many applications, these systems must accommodate large variations in gas flow rate, composition, heating value, and supply pressure while maintaining high destruction efficiency and avoiding visible emissions. At the same time, regional air districts continue to lower allowable emissions of NO_x, CO, and VOCs from combustion equipment, creating a need for retrofit technologies that can meet stringent permit requirements without wholesale replacement of existing flare infrastructure.

The retrofit project described in this paper was undertaken for an existing enclosed flare at an industrial oilfield facility in California. The existing unit required upgrades to meet regional air district permit requirements of 0.018 lb/MMBtu NO_x, 0.008 lb/MMBtu CO, and 0.0027 lb/MMBtu VOC, corrected to 3% O₂ on a dry basis. The design challenge was compounded by a low-pressure waste gas supply, a broad flow requirement of 250–450 MSCFD, and variable heating values from approximately 710 to 1150 Btu/SCF. These conditions create competing demands for mixing, flame stability, residence time, temperature control, and emissions minimization.

This paper combines the design basis, CFD evaluation, and commissioning results for the retrofit burner system using ClearSign's Core™ technology.

ClearSign's Core burner technology for process burners combines the benefits of lean Premixed Combustion and Internal Fuel Gas Recirculation to provide extremely low NO_x emissions, on the order of those achieved by more complicated and costly Selective Catalytic Reduction (SCR) system, and without the use of expensive catalysts or chemicals. Premixing the fuel and air to form fuel-lean mixtures avoids high temperature stoichiometric conditions in the flame zone and prevents conditions conducive to both prompt and thermal NO_x formation. Operation at higher excess-air levels can further suppress NO_x formation in ClearSign Core burners by producing a leaner air-fuel mixture, even after emissions are corrected for O₂ dilution.

ClearSign Core burner technology incorporates a distal flame holder positioned downstream from the air-fuel injection plane. Fuel and air are thoroughly mixed before reaching the flame holder. In addition, the momentum of the flow is utilized to internally entrain and recirculate the flue gases. The effect is dilution of the air-fuel mixture with inert flue gases – N₂, CO₂ and H₂O – which further lowers the flame temperature and reduces the

formation of thermal NO_x. The mixture is then ignited by the flame anchored at the flame holder location where the bulk of the combustion occurs. The burner technology has already been successfully applied to different applications – boilers, refinery process heaters, midstream hot-oil heaters, and enclosed flares. ClearSign Core boiler and midstream burners are forced draft while the process burners and enclosed flares can be natural or forced draft.

2. Design Requirements and Operating Envelope

The flare retrofit application was required to burn the specified waste-gas compositions over the full design operating range while utilizing the existing enclosed stack, with an inside shell diameter of 90 in. and an approximate height of 30 ft. Waste-gas compositions considered in the design covered low-, average-, and high-LHV cases. Methane was the dominant fuel species in each case, with carbon dioxide dilution varying significantly across the operating range and heavier hydrocarbons increasing in the high-LHV case. The gas compositions were simplified for simulation per Table 1 below and represent the range of LHV encountered in the application. The maximum heat release rate based on the highest flow rate and highest LHV was 25 MMBtu/h. Waste gas pressure available at the burner at high flow was 0.25 psig. The permitted emissions limits for the application were (on HHV basis):

- Guaranteed NO_x of 0.018 lb/MMBtu
- Guaranteed CO of 0.008 lb/MMBtu
- Guaranteed VOC (Volatile Organic Compounds) 0.0027 lb/MMBtu

Table 1 - Simulated waste-gas composition and flow rates.

Component / Parameter	Unit	Low LHV – HPI HP Flare	Average LHV – HPI HP Flare	High LHV – HPI HP Flare
Nitrogen (N ₂)	Mole%	0.33	1.06	0.65
Carbon Dioxide (CO ₂)	Mole%	23.68	8.75	8.07
Methane (CH ₄)	Mole%	73.43	80.08	67.50
Ethane (C ₂ H ₆)	Mole%	2.34	6.39	4.43
Propane (C ₃ H ₈)	Mole%	0.11	3.60	19.17
Water (H ₂ O)	Mole%	0.089	0.089	0.14
LHV	Btu/SCF	710	921	1,145
Simulated Flow (Wet) – Case 1	MSCFD	250	334	250
Simulated Flow (Wet) – Case 2	MSCFD	334	—	450
Simulated Flow (Wet) – Case 3	MSCFD	450	—	—

3. Retrofit Burner and Flare System Design

Given the extremely low pressure for the waste gas, a forced-draft burner system was designed to allow the momentum of the combustion air to provide the mixing energy for fuel-air premixing as well as flue gas entrainment. The burner design incorporated all the elements of the ClearSign Core technology. Combustion air was introduced via a blower and mixed with the waste gas in a pipe section before discharging into the stack. Waste gas was injected into the premixing pipe through a proprietary mixing apparatus. A star-shaped lobed discharge enhanced fuel-air mixing and generated a more uniform mixture at the distal flame holder plane.

The flameholder was supported at a fixed distance downstream of the lobed exit and was designed to promote flame stabilization and recirculation while maintaining stable combustion over turndown. An always-on pilot rated at approximately 80,000 Btu/h provided ignition energy for startup. Additional raw gas lances, that redirected a part of the waste gas flow to two pipes with ports directed towards the flameholder, were used to provide additional stabilization and locally increase temperature near the flameholder to reduce CO emissions.

The momentum of the fuel-air mixture from the lobed discharge entrained flue gases for additional dilution. Existing cutouts at the base of the stack were repurposed into two manually adjustable air doors to provide secondary air flow to the flame holder. The layout of the burner system and stack are presented in Figure 1 and Figure 2.

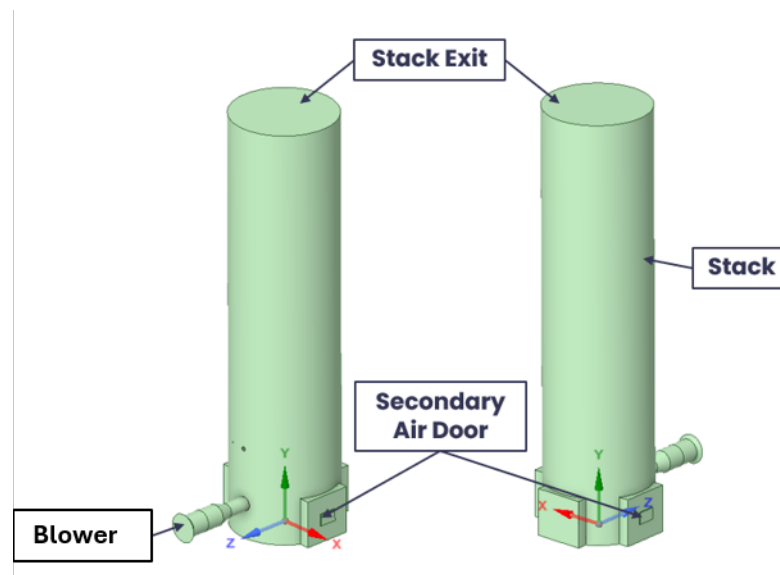


Figure 1 - Enclosed Flare Stack Layout

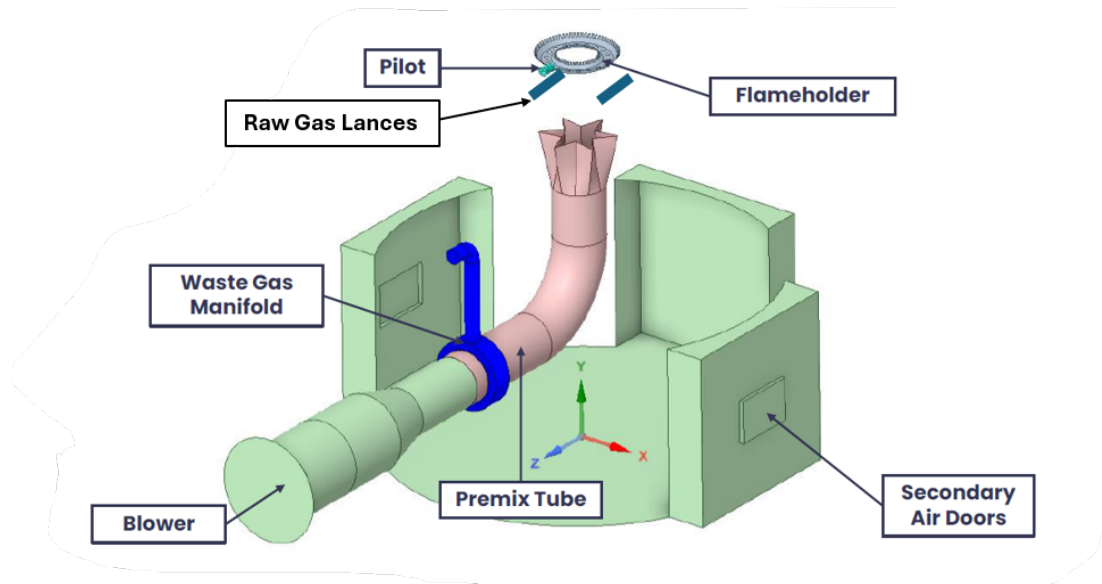


Figure 2 - ClearSign Core Burner Layout

4. CFD Modeling Approach

Six CFD operating points were selected to span the operating envelope. The low-LHV case was evaluated at 250, 334, and 450 MSCFD; the average-LHV case was evaluated at 334 MSCFD; and the high-LHV case was evaluated at 250 and 450 MSCFD as outlined in Table 1. These cases were selected to capture the minimum, midrange, and maximum waste-gas flows as well as the range of required combustion air demand and heat release.

CFD simulations were performed using Simcenter STAR-CCM+ 2406, version 19.04.007, in double precision. The simulations solved steady-state Reynolds-Averaged Navier-Stokes equations with the realizable k - ϵ turbulence model and two-layer wall treatment. Detailed gas-phase chemistry was simulated.

The waste-gas and pilot boundaries were modeled as mass-flow inlets. Waste-gas inlet flow rate and composition were set according to each operating condition. The pilot was modeled with combustion products at the inlet. Blower and secondary-air openings were modeled as stagnation pressure inlets. A blower interface based on manufacturer performance data determined the primary air delivery as a function of blower speed and included swirl representative of the axial blower.

The stack wall was modeled with a thermal conductivity, emissivity, an external heat transfer coefficient and ambient temperature. Participating-media radiation was included to capture radiative heat transfer.

The CFD model boundary conditions are shown in Figure 3.

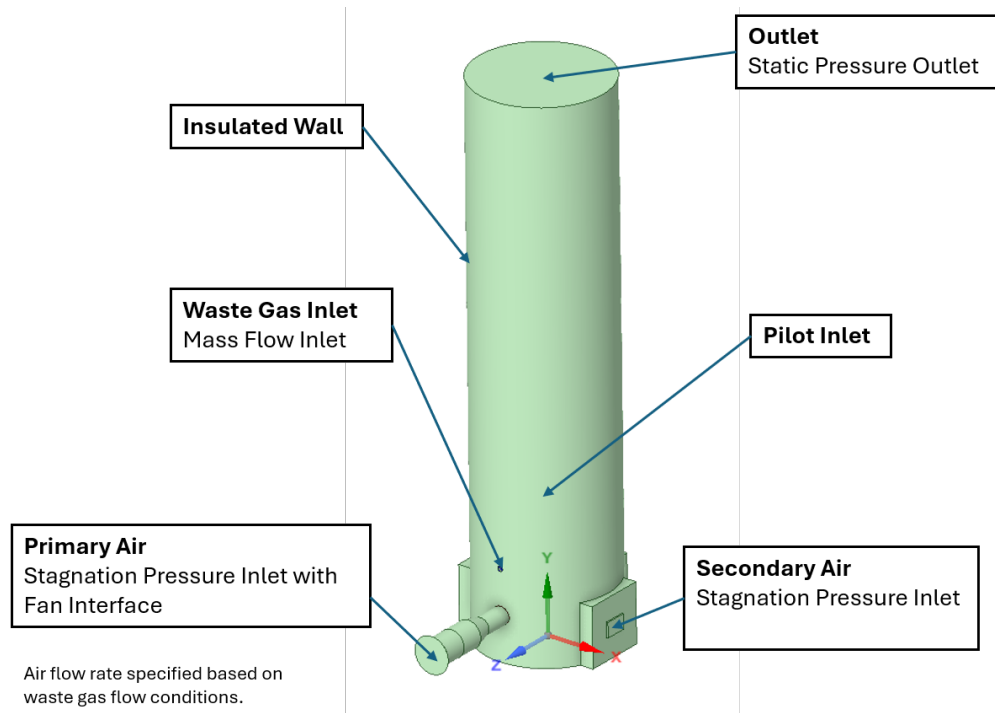


Figure 3 - CFD Boundary Conditions

5. CFD Results

The CFD results showed stable flame attachment at the downstream flameholder for all simulated operating conditions. Temperature contours through the central planes indicated broadly uniform combustion within the stack, with localized peak temperatures near the flameholder. OH iso-surfaces, used as a marker of the active reaction zone, showed circumferentially distributed and attached flames without evidence of lift-off or flame escape from the stack. The maximum predicted flame length remained within the enclosed volume, with the longest flame extending approximately 19 ft from the base of the stack.

Temperature and OH iso-surface contours for a few of the CFD cases are presented in Figure 4 and Figure 5. Across both low- and high-flow conditions, the higher-LHV fuel case remained more closely anchored to the flameholder than the lower-LHV case. A likely contributing factor was the greater heat release associated with the higher-LHV fuel at a given flow rate, which enhanced flame stabilization within the recirculation zone and maintained a more attached flame structure. The lower-LHV case exhibited a more lifted flame configuration along the outer edges of the reaction zone, where the flame front was located farther downstream relative to the flameholder. However, combustion remained stable for all cases considered.

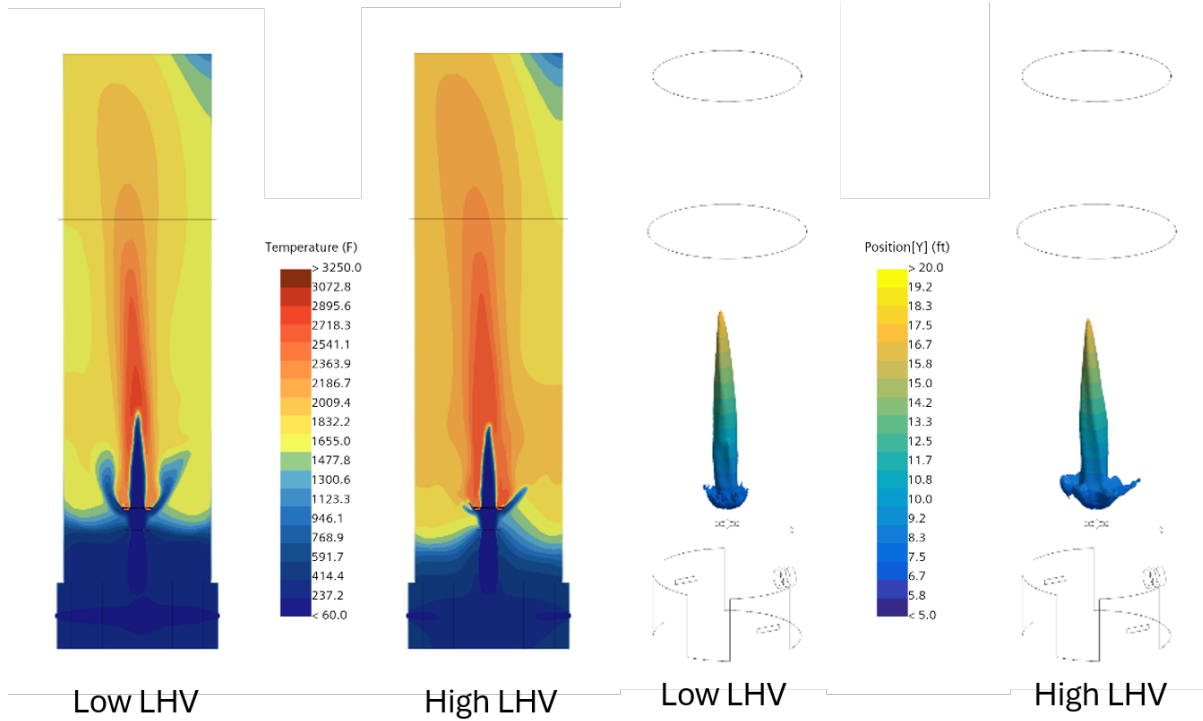


Figure 4 - Midplane Temperature Profiles (left) and OH Iso-surface Contours (right) for high waste gas flow case (450 MSCFD)

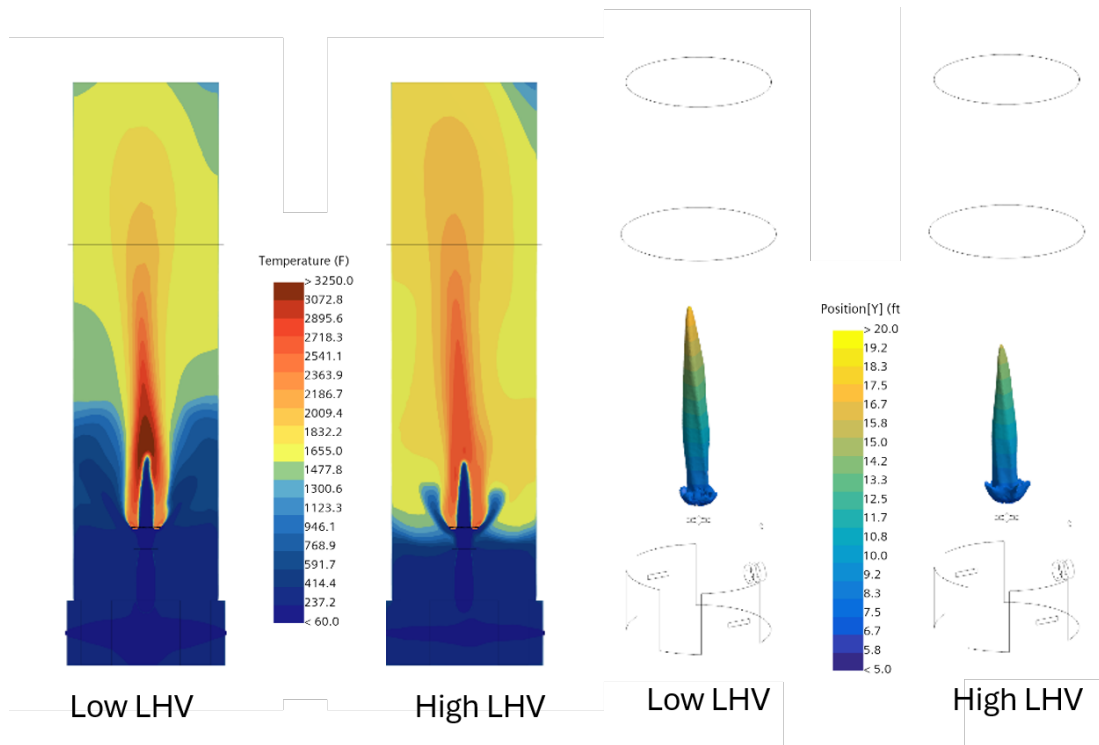


Figure 5 - Midplane Temperature Profiles (left) and OH Iso-surface Contours (right) for low waste gas flow case (250 MSCFD)

Predicted emissions were calculated at the plane corresponding to the intended thermocouple and emissions-probe location. The simulations predicted VOC below 0.00135 lb/MMBtu and CO below 0.004 lb/MMBtu for all simulated cases. Predicted NO_x was below 0.009 lb/MMBtu for most cases and 0.015 lb/MMBtu for the low-LHV 250 MSCFD case, remaining below the design guarantee of 0.018 lb/MMBtu. The CFD results demonstrated that the principal elements of ClearSign Core technology—lean premixing, internally induced flue-gas recirculation, and downstream flame stabilization—were effective in extending low-emissions combustion across the specified low-pressure waste-gas operating cases.

6. Proposed Control Methodology

A temperature-controlled variable frequency drive (VFD) was proposed to regulate the blower motor. Based on the CFD results, a stack exit-temperature set point of was selected as the target operating condition for optimum flare performance. The VFD would modulate blower speed to maintain this temperature by adjusting the combustion-air flow rate. The estimated air flow rates and exit temperatures (shown normalized) below in Figure 6 were modeled using 1-D simulations in DWSIM software and were later validated in the CFD modeled cases.

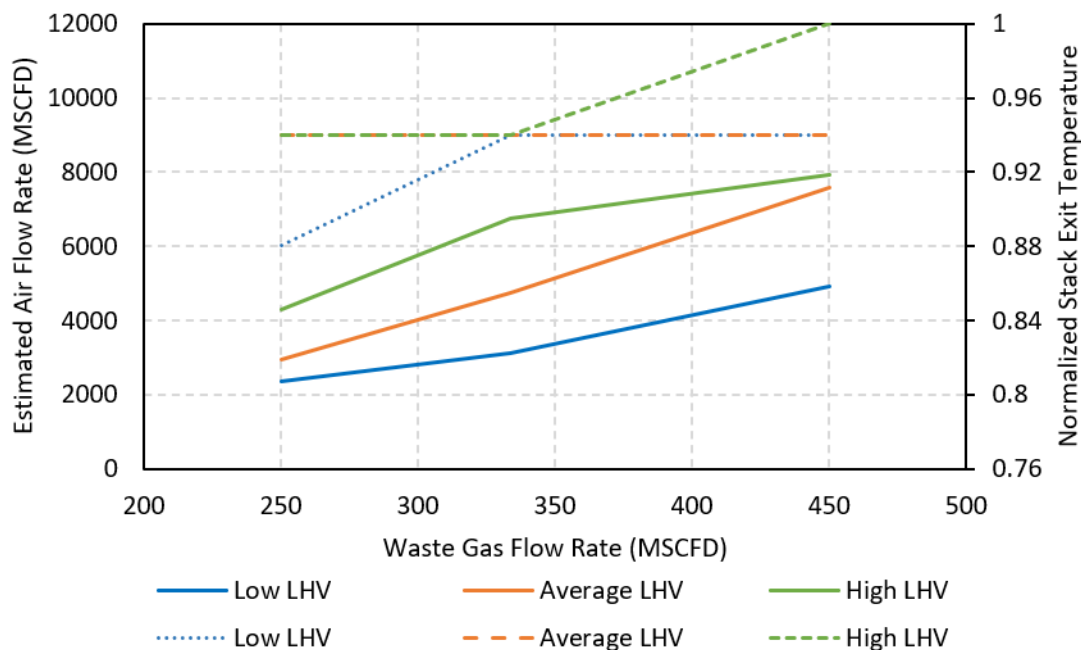


Figure 6 - Estimated Combustion Air Flow Rates and Corresponding Stack Outlet Temperatures

7. Commissioning, Implemented Control Methodology, and Field Tuning



Figure 7 – Burner Installed in the Enclosed Flare Stack

Figure 7 shows a photograph of the burner installation. The commissioning effort focused on confirming reliable ignition, stable flame anchoring, and emissions performance under expected operating conditions. The observed flame appearance and anchoring during commissioning was consistent with the CFD-predicted attached reaction zone, represented by the hydroxyl radical (OH) iso-surface, as shown in Figure 8.

During startup, it became clear that the originally proposed stack exit-temperature control philosophy would be challenging because of non-uniform temperatures near the stack exit and the slow response of the stack thermocouple. In addition, large deviations from the required air flow rate at a given waste-gas flow rate either increased CO emissions at the lean limit or allowed the flame to propagate upstream of the flameholder at the rich limit. As a

result, waste-gas flow rate was adopted as the basis for feed-forward control instead of temperature-based feedback, simplifying implementation relative to the originally proposed approach. The resulting blower VFD control curve was implemented into the site DCS (Distributed Control System) and is shown below in Figure 9. To account for variations in waste-gas composition as well as seasonal changes in ambient conditions, an additional O₂ trim was added using a stack-mounted O₂ analyzer.

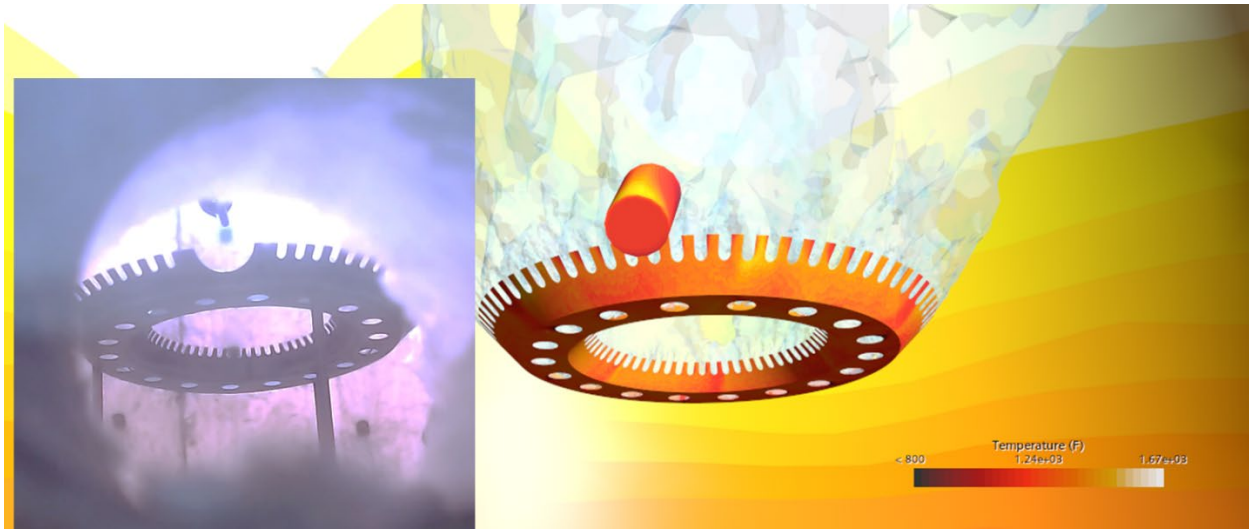


Figure 8 - Comparison of CFD-predicted flame structure (OH iso-surface) and observed flame appearance during commissioning

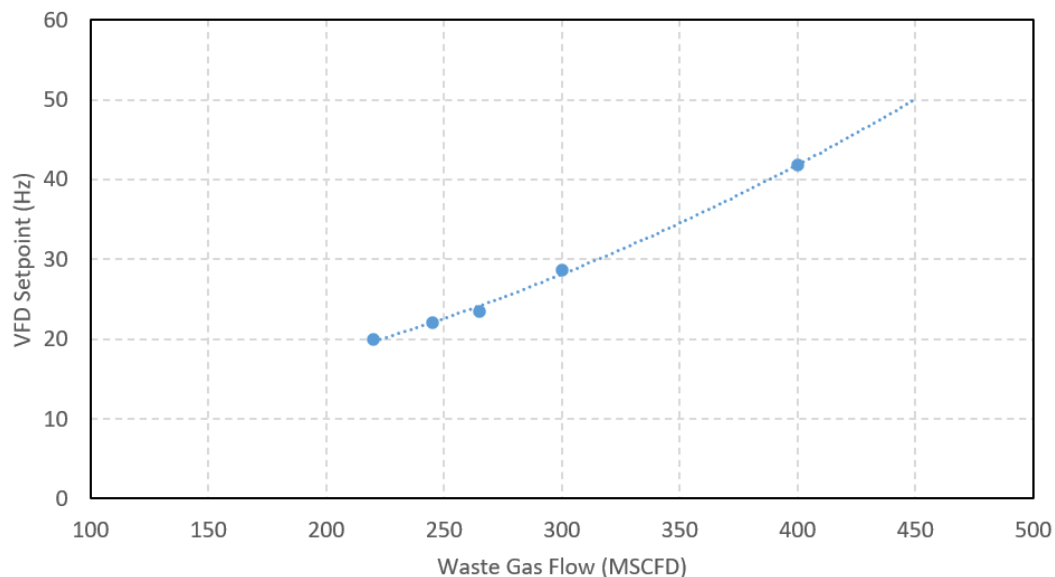


Figure 9 - Combustion Air (VFD) Control Curve

Emissions were tuned by adjusting the air flow rate, the secondary air doors, and the flow diverted to the raw gas lances. NO_x emissions, corrected to 3% O₂, decreased as air flow was

increased, which was consistent with the expected behavior of a premixed flame. Increasing the proportion of raw gas flow locally raised flame temperatures near the flameholder and reduced CO emissions but also increased NO_x emissions. Ultimately, NO_x and CO emissions were tuned well below the permitted limits, and no VOCs were detected. The secondary air doors and raw gas lances were then permanently fixed in position after commissioning. Final measured emissions are presented in Table 2. The observed difference in the stack O₂ between the portable analyzer and source test equipment was likely attributable to variations in probe location and insertion depth, as well as expected stratification of flue gas flow within the stack.

Table 2 - Final Emissions Results

	Stack O₂	NO_x			CO	VOC
	(%, dry)	(ppm, raw)	(ppm @ 3% O ₂)	lb/MMBtu (HHV)	lb/MMBtu (HHV)	lb/MMBtu (HHV)
Portable Emissions Analyzer	13.5	3.3	7.9	0.0096	0	0
Official Source Test	15.1	3.4	10.4	0.0126	0	0

8. Conclusions

The CFD, commissioning, and source test results demonstrated that the retrofit enclosed flare burner achieved ultra-low emissions while maintaining reliable operation under low-pressure flare conditions. The proprietary lobed mixer, distal flameholder, and distributed waste-gas injection strategy provided effective mixing, stable flame anchoring, and complete combustion across a broad operating range. Commissioning confirmed the importance of local mixing and flameholder temperature control for performance optimization. Final source testing confirmed compliance with all applicable permit requirements for NO_x, CO, and VOC emissions, validating the overall design approach. The results demonstrate that ClearSign's Core burner technology offers a practical and scalable retrofit solution for meeting stringent enclosed flare emissions requirements while retaining existing infrastructure.