EMISSIONS TESTING OF SONIC VELOCITY FLARES VALIDATES HIGH DESTRUCTION AND REMOVAL EFFICIENCY

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Abstract

In a 2012 report by the EPA's Flare Review Panel, regulations for flares that tended to operate outside their stable flame envelope were expanded to include limits on velocity as a function of net heating value.

EPA regulations do not currently allow sonic velocity flares to be permitted and operated without first performing an alternate means of emissions limitation tests to validate destruction efficiencies. Existing regulations affect the application of multi-point staged flares since these flares operate at sonic exit velocities that exceed the maximum exit velocity requirements cited in 40 CFR 60.18 and 40 CFR 63.11(b) and applicable state regulations.

Over the years, Zeeco has conducted numerous destruction efficiency tests on its multi-point sonic flares. All tests demonstrated high destruction efficiency at velocities exceeding the EPA's limits. The purpose of these tests, performed at Zeeco's industrial-scale combustion test facility near Tulsa, Oklahoma, was to validate sonic tips for more applications using an expanded range of gases and conditions. Extractive sampling was used to measure the emissions from the exhaust plume at staging and de-staging pressures. The extracted gas concentrations were used to calculate the destruction efficiency of the multi-point sonic flare tips at each test point. Even with sonic gas exit velocities, the Zeeco-designed sonic flare tips maintained high destruction efficiency.

Despite pressure from both end users and regulators, Zeeco's flare burner tests and results have been maintained internally. This paper will present those results to the industry.

Benefits and Characteristics of Multi-Point Ground Flares

Multi-Point Ground Flares (MPGF) derive their name from their physical layout. Typically, they are a field of multiple pressure-assisted flare tips that are vertically mounted at grade and arranged in stages that open as the upstream pressure (gas flow) increases, and close as pressure decreases. This design concept is the same today as it was when MPGF were invented over 40 years ago. MPGF are often selected to attain smokeless combustion for heavy hydrocarbon service with high available pressure, and have proven to provide stable operation at sonic velocities for a wide range of gas compositions. MPGF are also used in situations when the designer wants to reduce or eliminate radiation or visible flame. The high pressure is used to assist the gas to obtain smokeless operation for the full range of flaring capacity, which can be difficult to do with other assist mediums such as air, gas, or steam due to high smokeless rates. Each burner has unobstructed air access, allowing the momentum from the high exit velocity of the flare gas to entrain the necessary air for combustion. MPGF are designed to provide maximum smokeless performance, while minimizing radiation impacts and plot space. Installing a fence around the field can block the visibility of the flame; this serves a dual purpose by reducing radiation outside the fenced area and reducing the likelihood that flaring operations will be a nuisance to the public. The figure below is an example of a typical MPGF installation.

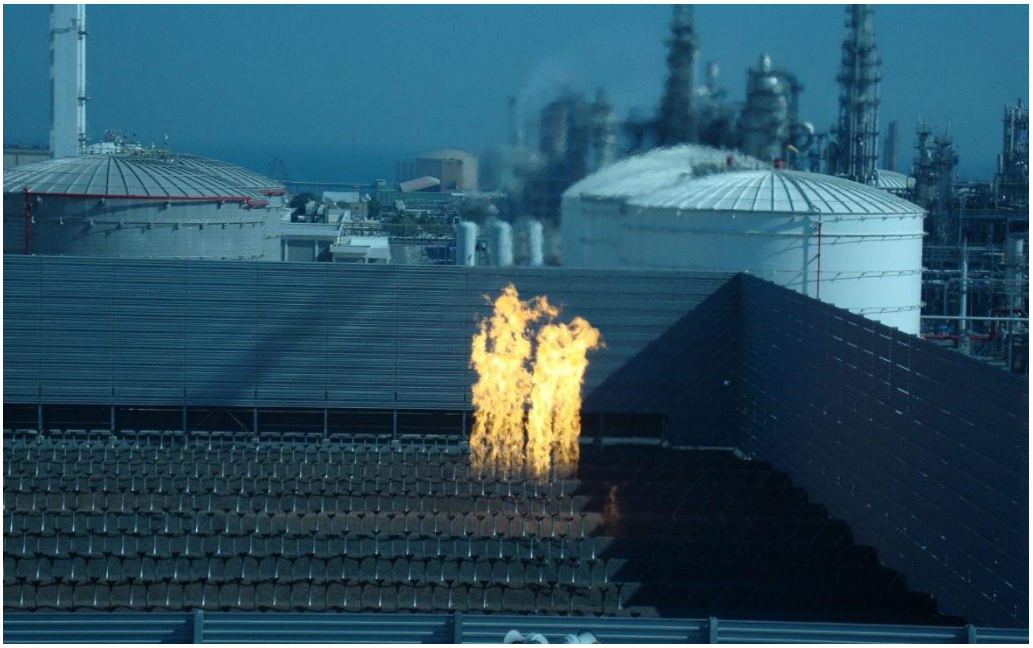

Figure 1 – Typical Installation of a MPGF

Another benefit of MPGF is easy access for maintenance because all staging equipment is located at grade and outside of the fence. As a result, personnel can access the staging equipment safely without being affected by a flaring event. Figure 2 illustrates the staging equipment and the exterior of a MPGF fence.

Figure 2 – Typical Installation of MPGF Fence

Over the past 40-plus years, there have been many improvements in burner technology. Zeeco's modern pressure-assisted tips are custom designed to optimize the mixing of flare gas and air thus improving tip performance. Zeeco's pressure-assisted flare tips, shown in Figure 3, are an investment casting typically made out of 310 SS casting material.

Figure 3 – Zeeco's Pressure-Assisted Flare Tip Casting

Multiple tips are arranged in stages to allow control over the number of tips in service, depending upon the pressure and flow rate of the flare gas. This enables the tips to operate in the optimal pressure range for maximum smokeless capacity. Each stage will open when the pressure in the MPGF header has increased to the designed staging pressure and subsequently close when the de-stage pressure is met. Figure 4 is an example of a typical staging curve used to control MPGF.

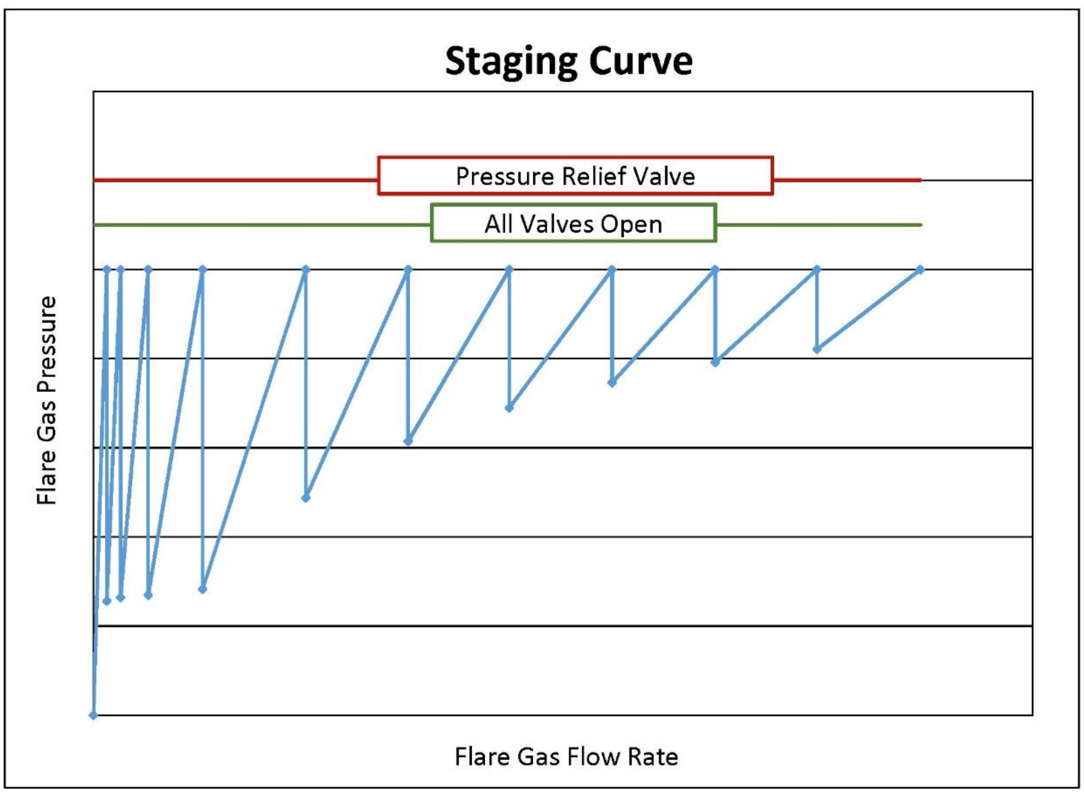

Figure 4 – Typical Staging Curve for MPGF

The staggered blue line in Figure 4 represents how the pressure in the system will change as each stage opens and closes. The high and low points of the blue line represent the staging and de-staging pressures for each stage, respectively. Typically, the staging pressure is equal to the available pressure of the system. However, it could be lower based on maintaining stable performance. When the pressure in the MPGF header reaches the designed staging pressure, the next stage of tips opens. The system is designed so the pressure in the open stages never decreases below a desired pressure. This is referred to as the de-staging pressure and generally corresponds to the minimum pressure required to ensure stable performance and smokeless combustion. A typical de-staging curve follows the same pattern as the staging curve, but closes the valves as the pressure in the MPGF header decreases.

Regulations and Industry Testing

Currently, federal and state regulations on flares limit the exit velocity of the flare gas based on the composition and LHV of the gas as well as the assist medium of the flare. There are three assist types considered by the regulations: non-assisted, steam-assisted, and air-assisted. According to the federal and state regulations, if a flare is operated within these velocity and LHV restrictions, a destruction and removal efficiency (DRE) of 98% or greater is guaranteed. This suggests that if a flare operates outside of these limits, it will result in lower DRE.

In 1983, flare efficiency testing was performed by the Chemical Manufacturers Association (CMA). Three types of flares were tested: air-assisted, steam-assisted, and non-assisted. It is important to note that pressure-assisted flares were not included in this testing. In the testing performed, extractive sampling was used to measure the concentrations of emissions from each flare to determine the combustion efficiency (CE). The results from this testing became the basis of the current regulations: 40 CFR 60.18 & 40 CFR 63.11. The CMA concluded if there was a stable flame, the flare had high CE.

From 1984-86, Energy and Environmental Research (EER) Corporation performed testing for the EPA to evaluate the combustion efficiency CE for a variety of gas compositions on different commercially available flare tips, including two pressure-assisted tips that were obtained from flare vendors. The pressure-assisted flare tips were referred to in the test report as Commercial Tips “E” and “F.” Commercial Tip E used a horizontal bar geometry while Commercial Tip F used an open geometry. The results showed that stable burning pressure-assisted tips operated at CE values of greater than 98%, even at high exit velocities.

In November 2013, Dow Chemical Company performed an Alternate Means of Emissions Limitation (AMEL) test for two of its MPGF installations. Nominal four-inch sonic burners were tested by extractive sampling to investigate the propylene DRE of two different flare tips, one of which was pressure-assisted. The results from this testing showed that the pressure-assisted tips were capable of providing greater than 98% DRE and CE over the range of gases that were tested. Furthermore, the testing confirmed that the presence of a stable flame ensured high DRE and CE. The conclusions and results were published and presented at the American Flame Research Committee (AFRC) Conference in 2014.

The current EPA regulations are based on the CMA testing in 1983; however, various other tests have been performed to further investigate pressure-assisted flare efficiency. These tests prove sonic flares can operate outside of the limits set by the EPA and still achieve high DRE.

Execution of Extractive Sampling

In addition to the testing previously described, Zeeco has conducted numerous destruction and removal efficiency tests on its MPGF pressure-assisted tips. All MPGF testing that is further detailed in this paper was conducted at the Zeeco Inc. Combustion and Research Test Facility in Broken Arrow, Oklahoma. The purpose of Zeeco's tests on MPGF was to investigate the destruction and removal efficiency and stability over a wide range of net heating values (NHV) and gas compositions. NHVs from 440 BTU/SCF to 2316 BTU/SCF were tested with gas mixtures, including the following: propane, propylene, natural gas, carbon dioxide, nitrogen, and hydrogen. Destruction and removal efficiency was determined by measuring the concentration of carbon dioxide (CO_2), carbon monoxide (CO), and total hydrocarbons (THC) from extractive sampling. An example of extractive sampling being performed on a single MPGF pressure-assisted tip is shown in Figure 5.

Figure 5 – Extractive Sampling Method Used for Testing

Zeeco's custom sample hood, shown in Figure 5, was used to extract combustion products from the plume. A Venturi nozzle located at the end of the apparatus created a vacuum for sample extraction. A crane was used to position the inlet of the sample hood in the plume of combustion products. The crane was directed by an operator who monitored the hood's position with respect to the plume using a forward looking infrared (FLIR) camera to ensure a proper sample was obtained. A continuous sample was pulled from the sample hood through a heated sample line to gas analyzers where the concentration of the combustion products was measured and recorded.

The concentrations of CO_2, CO, and THC were used to calculate destruction and removal and combustion efficiency. DRE and CE are two ways of quantifying the degree of completion of the combustion reaction based on measured emissions. DRE is how well a component of interest is destroyed or broken down according to the amount of unburned hydrocarbons after the combustion process is completed. Alternatively, CE is how well a component of interest is converted into CO_2 and H_2O after the combustion process. The hydrocarbon DRE and CE equations are shown below.

$$DRE_{THC}(\%) = \frac{CO_2 + CO}{CO_2 + CO + THC} \cdot 100\%$$

$$CE(\%) = \frac{CO_2}{CO_2 + CO + THC} \cdot 100\%$$

It is important to understand the difference between both values to properly interpret the results. The CE is equal to or less than the DRE since the component of interest may be destroyed, but not completely combusted. The component of interest can reduce to an intermediate combustion product instead of completely combusting and forming only CO_2 and H_2O. To summarize, generating proportionally high CO_2 will result in high CE, while generating proportionally low hydrocarbons will result in high DRE. For conservative results, the DRE and CE of total hydrocarbons were observed to verify that all hydrocarbons were being combusted.

Results

The following results are from numerous tests performed at Zeeco from 2013 to 2015. Gas mixtures with NHVs ranging from 440 to 2316 BTU/SCF were tested on a single piloted sonic flare tip to investigate the effect of NHV on flame stability and efficiency. The maximum allowable exit velocity per 40 CFR 60.18 is based on the NHV of the flare gas. For NHVs ranging from 200 BTU/SCF to 1000 BTU/SCF, an exponential function limits the exit velocity from 45.7 ft/s to 400 ft/s. For NHVs greater than 1000 BTU/SCF, the maximum allowable exit velocity remains 400 ft/s. Every gas was tested at exit velocities that exceeded the limits defined by 40 CFR 60.18. As long as the flame was stable, DRE and CE values greater than 99% were consistently observed.

Figure 6 illustrates the high destruction and removal efficiencies obtained outside of the 40 CFR 60.18 operating limitations.

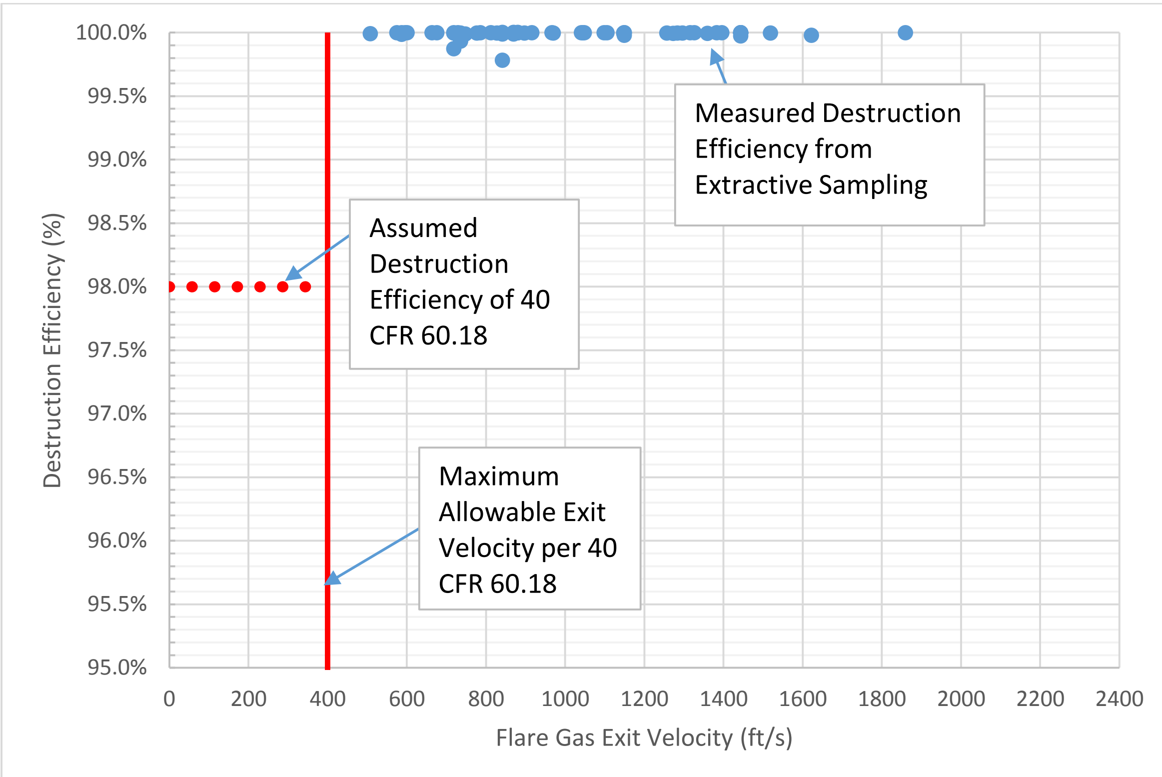

Figure 6 – Destruction and Removal Efficiency vs. Flare Gas Exit Velocity

The information in Figure 6 represents a total of 64 test runs. Flare gas mixtures ranged from molecular weight (MW) of 6.58 to 44.1 and from NHVs 440 to 2316 BTU/SCF. The mixtures were tested at operating pressures from 3 to 30 psig. The total compilation of all data was minimized by omitting the bottom 6% of the DRE values. The omitted test points will be discussed later.

Every gas combination tested that maintained a stable flame operated with high efficiencies despite the flare gas exit velocity exceeding the limits set forth in 40 CFR 60.18. The results from these tests on Zeeco's pressure-assisted tips prove that pressure-assisted flares should not have these exit velocity restrictions.

Several tests were performed to investigate the stability and effect of hydrogen (H_2) in hydrocarbon gas mixtures. The NHVs of the mixtures ranged from 440 to 1076 BTU/SCF with hydrogen mole percents between 25% and 70%. All gas mixtures were tested at exit velocities between 0.6 Mach (777 ft/s) and 1.0 Mach (2408 ft/s). Throughout the testing with H_2, the flame remained stable and attached to the tip and resulted in DRE and CE values of 99% or higher.

According to 40-CFR 60.18, an alternate method of calculating maximum exit velocity can be used for flare gas with a H_2 volume percent of 8.0 or greater. This alternate method linearly varies maximum exit velocity based on H_2 content between 8.0 percent at 25.6 ft/s and 15.6 percent at 122 ft/s and limits all volume percents greater than 15.6 to 122 ft/s. All of the H_2 mixtures tested had greater than 15.6 volume percent of H_2 and per 40 CFR 60.18 would be required to have an exit velocity less than 122 ft/s to meet the current EPA regulations. The results from Zeeco testing show that exit velocities greater than 122 ft/s did not negatively impact the flare efficiency for the H_2 mixtures tested. Although adding H_2 typically lowers the NHV of a gas mixture, testing showed that the presence of H_2 improved the stability of the flame compared to similar NHV mixtures without H_2. The benefit of H_2 flammability outweighed the downside of the reduced NHV, yielding high efficiencies.

The only unstable flame observed was when burning a gas mixture of propylene and nitrogen with an NHV of 600 BTU/SCF. This gas case was unable to maintain stability at the pressures tested and exhibited substantially lower DRE and CE than all other cases. In comparison, a mixture of natural gas and nitrogen with a NHV of 600 BTU/SCF remained stable at the pressures tested and maintained DRE and CE values above 99%. This suggests efficiency is not solely dependent upon the NHV of the flare gas. The difference in efficiency could be attributed to the volumetric ratio of flammable gas versus inert gas. In order to bring the NHV of a propylene mixture down to 600 BTU/SCF, a higher volume of inert gas is needed compared to a natural gas mixture. For example, the propylene mixture had approximately 73% volume inert gas where the natural gas mixtures had approximately 35% volume of inert gas. The higher volume of inert gas could be the cause of the lower efficiency.

Additional testing performed by Zeeco included the use of Passive Fourier Transform Infrared (PFTIR) in parallel with extractive sampling to measure CE. Four tests of propane, propylene, natural gas, and a propane and nitrogen mixture were used for this comparison. A similar exercise was conducted for Zeeco’s new technology, FlareSentry™. FlareSentry’s measurement results repeatedly matched the results from the extractive sampling method within 0.44%. All methods showed all four gas compositions had high CE while operating at sonic exit velocities as shown in Figure 7.

Gases	C3H8	C3H8/N2	C3H6	NG
NHV (BTU/SCF)	2316	1251	2183	937
40 CFR Maximum Allowable (ft/s)	400	400	400	400
Exit Velocity (ft/s)	841.4	969.9	869.8	1443.5
Mach Number	1.00	1.00	1.00	1.00
Flare Operating Pressure (psig)	16.0	10.3	16.9	15
CE (%) from Extractive Sampling	99.99%	99.99%	99.96%	99.99%
CE (%) from PFTIR	99.60%	99.90%	99.60%	99.50%
DRE (%) from Extractive Sampling	99.99%	99.99%	99.99%	99.99%
DRE (%) from FlareSentry	99.80%	99.55%	99.90%	99.70%

Figure 7 – Comparison of PFTIR and FlareSentry vs. Extractive Sampling Method

FlareSentry is a multi-spectral infrared imager based flare monitoring technology that remotely measures the DRE of flares. Its remote mounting enables it to be located in non-hazardous areas where it is easily accessible. The unique capabilities of this new technology allow for continuous and autonomous monitoring of DRE with no operator input or calibration required. There is no need for continuously "aiming" the device at a certain region of the flare plume like some DRE measurement techniques, nor does the technology require a knowledge of the gas composition for its calculations. FlareSentry can also monitor the presence of a pilot flame and provide a smoke index that can be used to predict the presence and degree of smoke in the combustion plume. Additionally, FlareSentry can use its smoke index to monitor and record the flare's operation, so the records may be used for reporting purposes. This eliminates the need to have personnel resources dedicated to smoke observation. FlareSentry will provide flare operators with real-time data to ensure optimal DRE while maintaining smokeless performance day or night. It also facilitates more precise and timely control of assist media and enrichment fuel, reducing utility costs. An industrial interface allows for integration with Distributed Control Systems (DCS) to enable closed loop operations. FlareSentry is a revolutionary new product that will redefine emissions monitoring and measurement for flares.

Conclusion

Multi-Point Ground Flares deliver smokeless flaring over a wide range of flows, compositions, and pressures while having minimal impact on surrounding communities. The testing conducted at the Zeeco Combustion and Research Test Facility investigated the effect of NHV and exit velocity on the stability and efficiency of Zeeco's pressure-assisted flare tips. All test results with stable flames demonstrate Zeeco's pressure-assisted flare tips provide high destruction and removal efficiency even at high exit velocities exceeding current regulatory limits. The extractive sampling results validated the performance of the new FlareSentry, which is pioneering a practical method of monitoring and measuring flare efficiency. This testing has reinforced the industry consensus that pressure-assisted flare tips are capable of providing smokeless flaring with high destruction and removal and combustion efficiencies over a wide range of gas compositions and pressures. Recommendations for future testing are to investigate the stability of lower NHVs over a range of pressures and exit velocities as well as the effect of different ratios of combustible to inert gases. Current and future regulations should consider all available test results and allow the use of pressure-assisted flares with high exit velocities, up to and including Mach 1.0, without the need to perform an AMEL.