A FLARE FOR THE DRAMATIC

Scot Smith, Zeeco, Inc., USA, describes how the emissions testing of sonic velocity flares validates high destruction and removal efficiency.

In a 2012 report by the US Environmental Protection Agency (EPA) Flare Review Panel, regulations for flares were expanded to include limits on velocity as a function of net heating value. EPA regulations do not allow sonic velocity flares to be permitted and operated without first performing an alternate means of emissions limitation (AMEL) test 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. Zeeco and others have conducted numerous destruction efficiency tests on multi-point sonic flares to validate sonic tips for more applications using an expanded range of gases and conditions. The testing process, procedures and results are outlined in this article.

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 mounted vertically at grade and staged to open as the upstream pressure from the gas flow to the flare installation increases. Flare tips close in stages as pressure decreases. The basic design concept has remained the same for more than 40 years. MPGFs are often used with the application that requires stable, smokeless combustion for heavy hydrocarbons with high available pressure. MPGFs are also used in situations where the designer wants to reduce or eliminate radiation or visible flame. High pressure is used to assist the gas to deliver smokeless operation over the full range of flaring capacity, which can be difficult to do with other assist mediums such as air, gas, or steam. Each tip has unobstructed air access, allowing the momentum from the high exit velocity of the flare gas to entrain the necessary air for combustion. MPGFs are designed to provide maximum smokeless performance, while minimising 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. Figure 1 shows an example of a typical MPGF installation.

Another benefit of MPGFs is easy access for maintenance, because all staging equipment is located at grade and outside 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 an MPGF fence.

While the basic concept of MPGFs has not changed, there have been many improvements in the technologies employed. Zeeco's modern pressure-assisted tips are custom designed to optimise the mixing of flare gas and air, thus improving tip performance. The flare tips, shown in Figure 3, are an investment casting typically made out of 310 SS casting material.

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

Figure 1. Typical multi-point groud flare installation.

Figure 2. Typical installation of MPGF fence.

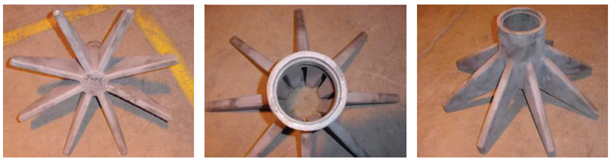

Figure 3. Zeeco's pressure-assisted flare tip casting.

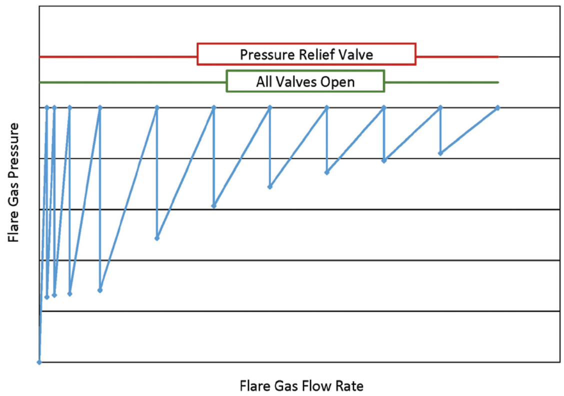

Figure 4. Typical staging curve for MPGF.

optimal pressure range for maximum smokeless capacity. Figure 4 is an example of a typical staging curve used to control 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, staging pressure is equal to available system pressure; 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 open. The system is designed so the pressure in the open stages never decreases below a certain level. The floor pressure level 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 previous industry testing

Currently, US federal and state regulations on flares limit the exit velocity of the flare gas based on the composition and lower heating value (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. Where did these regulations and assumptions originate?

In 1983, the Chemical Manufacturers Association (CMA) performed flare efficiency testing on three types of flares: air-assisted, steam-assisted and non-assisted. It is important to note that pressure-assisted flares were not included. The CMA used extractive sampling 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 and 40 CFR 63.11. The CMA concluded if there was a stable flame, the flare had high CE.

From 1984 - 1986, Energy and Environmental Research (EER) Corporation performed testing for the EPA to evaluate the CE for a variety of gas compositions on different commercially available flare tips, including two pressure-assisted designs. 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 AMEL test for two of its MPGF installations. Nominal four in 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.

Current EPA regulations are based on the CMA testing performed in 1983, but various other tests have been performed since that time proving sonic flares can operate outside the limits set by the EPA, while still achieving high DRE.

Execution of extractive sampling DRE tests

In addition to the testing previously described, Zeeco has conducted numerous DRE tests on its MPGF pressure-assisted tips at the company's Combustion and Research Test Facility in Broken Arrow, Oklahoma, USA. The goal of the extensive testing programme 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 - 2316 Btu/ft^3 were tested with gas mixtures, including the following: propane, propylene, natural gas, carbon dioxide, nitrogen and hydrogen.

DRE 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.

A Venturi nozzle located at the end of the apparatus created a vacuum for sample extraction and a crane was used to position the inlet of the sample hood in the plume of combustion products. An operator directed the crane and monitored the hood's position with respect to the plume using a forward-looking infrared (FLIR) camera to ensure a proper sampling. A continuous extraction was pulled from the sample hood through a heated sample line to gas analysers 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:

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

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

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 summarise, 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 by Zeeco from 2013 to 2015. Gas mixtures with NHVs ranging from 440 - 2316 Btu/ft^3 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 - 1000 Btu/ft^3, an exponential function limits the exit velocity from 45.7 - 400 ft/s. For NHVs greater than 1000 Btu/ft^3, 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.

The information in Figure 6 represents a total of 64 test runs. Flare gas mixtures ranged from molecular weight of 6.58 to 44.1 and from NHVs 440 to 2316 Btu/ft^3. The mixtures were tested at operating pressures from 3 - 30 psig. The total compilation of all data was minimised 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 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 - 1076 Btu/ft^3 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).

Figure 5. Extractive sampling method used for testing.

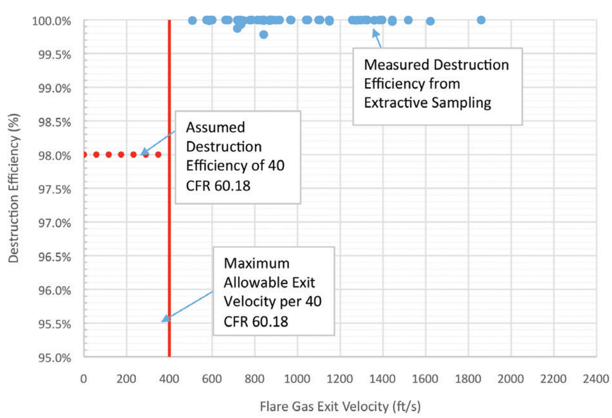

Figure 6. Destruction and removal efficiency versus flare gas exit velocity.

Table 1. Comparison of PFTIR versus extractive sampling method

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 optical testing	99.80%	99.55%	99.90%	99.70%

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% at 25.6 ft/s and 15.6% at 122 ft/s and limits all volume percents greater than 15.6 - 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 tests 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 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 flaring a gas mixture of propylene and nitrogen with NHV of 600 Btu/ft^3. 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/ft^3 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/ft^3, 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 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 an optical-based flare monitoring technology, which remotely measures the DRE of flares. Results from the optical-based testing were extremely close to the results from the extractive method. All methods showed all four gas compositions had high CE while operating at sonic exit velocities as shown in Table 1.

Conclusion

MPGFs deliver smokeless flaring over a wide range of flows, compositions, and pressures with 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. All test results with stable flames show high destruction and removal efficiency even at high exit velocities exceeding current regulatory limits. 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.