Scot Smith and Christopher Filoon, Zeeco, USA, explain how the employment of direct flame monitoring technology can help operators comply with increasingly stringent flaring regulations.

SCORCHING SOLUTIONS

Over the years, the US Environmental Protection Agency (EPA) has been actively involved in various flare enforcement initiatives, as flares can be a significant source of emissions. EPA actions include enforcing a number of consent decrees, establishing standards for proper destruction removal efficiencies (DRE), and supporting environmental group civil suits against end users. On 30 June 2014, the EPA proposed revisions to the National Emissions Standards for Hazardous Air Pollutants (NESHAP) for petroleum refineries to include flare monitoring and operational requirements, and to mandate that flares serving as control devices at petroleum refineries achieve a minimum destruction efficiency of no less than 98%. The EPA then consolidated those efforts into a final rule known as 40 CFR Parts 60 and 63. The new refinery regulation was published in the Federal Register on 1 December 2015, making the effective date of the regulation 1 February 2016, and the compliance deadline 31 January 2019.

Unlike other emission sources, combustion in an industrial flare occurs in open air, so it does not allow for a practical method to directly monitor post-combustion flare gases. Current combustion efficiency (CE) flare monitoring methods include the extractive method (directly sampling post-combustion flare gases), open path Fourier Transform Infrared spectroscopy (FTIR), and the use of surrogate parameters (e.g., heating value, exit velocity) to indirectly predict CE. Monitoring flare performance using open path FTIR and extractive methods is not practical for continuous monitoring, as confirmed by the EPA in the recent refinery rule documentation, while the monitoring of indirect parameters is inadequate, complex and costly.

Flare manufacturers take a number of process parameters into account when designing flares so they combust at least 98% of the hydrocarbons being supplied to the flare tip, optimising CE. Flare manufacturers provide plant operators controls to optimise flare operation by adjusting the steam to vent gas ratio, adding supplemental fuel, or changing the fuel to air ratio. However, actual flare emissions and CE are typically estimated after the fact based on input streams, combustion equations and indirect measurements, such as the speciation of the waste stream, are sent to the flare. There is a need for a real time post combustion measurement of CE, which could be used by plant operators to maintain optimal flare performance.

Figure 1. FlareSentry™ unit.

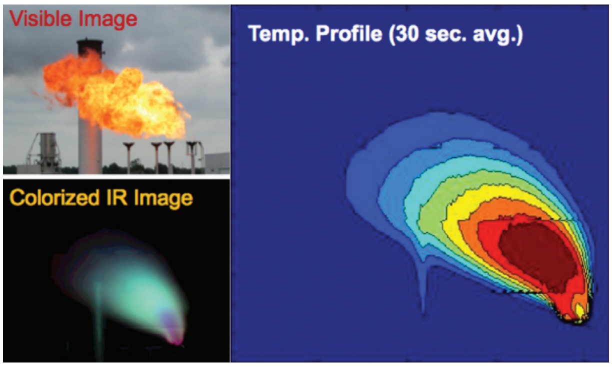

Figure 2. Comparison of visible, infrared and averaged profile images.

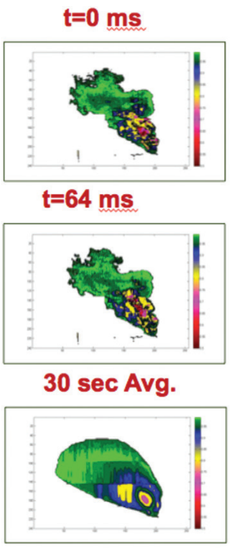

Figure 3. Comparison of pixel images over time.

When post combustion gases can be accurately measured, flare CE is typically determined by the following equation, where CE (%) is the combustion efficiency, expressed as a percentage.

- Equation one:

$$CE(\%) = \frac{[C]_{CO2}}{\sum_i n_i[C]_{HCi} + [C]_{CO} + [C]_{CO2}} \times 100$$

Where: CO_2 = the volume concentration of CO_2 in the plume once combustion has ceased; CO = the volume concentration of carbon monoxide (CO) in the plume once combustion has ceased; HCi = the volume concentration of the *i*th hydrocarbon (HC) compound remaining in the plume once combustion has ceased; n_i = the number of carbon atoms in the *i*th HC compound; and i = the *i*th hydrocarbon compound in the flare vent gas. When there is only one compound, *i* = 1.

When there is no unburned HC (HC_i = 0) and no product of incomplete combustion, such as CO in the plume (CO = 0), the combustion is complete and CE is 100%. Under most common conditions, the concentration of CO as a product of incomplete combustion is measured in orders of magnitude lower than either CO_2 or HC. For this reason, CO can be neglected in the CE calculation. Therefore, equation one becomes equation two.

- Equation two:

$$CE(\%) = \frac{[C]_{CO2}}{\sum_i n_i[C]_{HCi} + [C]_{CO2}} \times 100$$

EPA rulings dictate the required DRE for flare systems, but, as shown in equations one and two, flare performance (as determined by destruction of HC) can be measured by CE. As equation two directly compares unburned HC and its ultimate combustion product (CO_2), the CE calculated by equation two can also be used as an approximation of DRE for HC – that is, how much HC is destroyed regardless of how much is in the CO stage.

The known shortcomings of current indirect monitoring methods, in combination with the new EPA standards and deadlines, drove the development of a new flare CE measurement and monitoring method – a technology that can be used to directly, autonomously and continuously monitor flare performance in real time.

The new method for flare CE measurement and monitoring was first proposed by Zeng, et al., in 2012 and has been proven through a series of large scale validation tests. It is based on a unique multi-spectral infrared (IR) imager that provides a high frame rate, high spectral selectivity and high spatial resolution (Figure 1).

The method can be deployed for short term flare studies or for permanent installation providing real time continuous flare CE monitoring. In addition to the measurement of CE, the method also measures and reports the level of smoke in the flare flame, regardless of whether it is day time or night time. The measurements of both CE and smoke levels provide the flare operator with a real time tool to identify and operate at the 'incipient smoking point' to optimise flare performance.

The multi-spectral IR imager simultaneously measures the relative concentrations of combustion products, CO_2 and unburned HC at the pixel level. The relative concentrations of CO_2 and HC levels measured at each pixel are used to calculate the CE for that pixel, which represents a path-averaged CE for a column of combustion gases represented by the pixel. A CE value for the overall flare, at any given moment, is calculated by averaging the CE values of the pixels that represent the outer layer of the combustion zone of the flare where combustion has ceased.

A CE value representing the flare at any given moment is calculated by averaging CE values of the pixels that represent the outer layer of the combustion zone of the flare. The imager has a high frame rate (11 - 30 frames/sec.) that results in a data acquisition cycle of 91 - 33 ms. The short data acquisition cycle means that the path length through the plume depth can be considered constant for each measurement (frame). This addresses the significant limitation of other imaging-based technologies with long data acquisition cycles (e.g., 1 sec. [Figure 3]). As the data acquisition cycle increases, the uncertainty due to the changing conditions (plume depth) increases and the accuracy of the result will suffer. This new method has been developed into the FlareSentry™, multi-spectral infrared (IR) imager – the first practical, autonomous, real time monitoring device for flare CE.

Table 1. Flare CE validation test results

Test no.	Flare type	Fuel	Fuel flow rate (lb/hr)	Stoichiometric air	Steam/HC (lb/lb)	CZNHV (Btu/ft^3)	CE-extractive method	CE-new method	CE difference	Smoke index	Avg. O_2 in extracted sample
1	AFDS	Propane (100%)	7994	33.29%		259	99.94%	97.40%	-2.54%	2.85	21.13%
2	AFDS	Propane (100%)	7994	33.29%		259	99.99%	98.80%	-1.19%	2.46	19.45%
3	AFDS	Propane (100%)	7994	33.29%		259	99.98%	98.70%	-1.28%	4.58	19.37%
4	AFDS	Propane (100%)	6670	39.89%		221	99.99%	98.80%	-1.19%	2.87	17.63%
5	AFDS	Propane (100%)	6670	39.89%		221	99.97%	98.60%	-1.37%	2.70	18.84%
6	AFDS	Propane (100%)	5278	50.42%		178	99.97%	99.20%	-0.77%	2.66	19.83%
7	AFDS	Propane (100%)	5278	50.42%		178	99.95%	99.20%	-0.75%	2.50	20.03%
8	AFDS	Propane (100%)	3063	86.87%		107	99.33%	99.00%	-0.33%	0.72	20.53%
9	AFDS	Propane (100%)	3063	86.87%		107	99.77%	98.70%	-1.07%	1.44	18.94%
17	QFS	Propylene (100%)	4910		0.48	1031	99.86%	99.00%	-0.86%	3.99	19.93%
18	QFS	Propylene (100%)	4910		0.48	1031	99.90%	99.10%	-0.80%	2.24	19.98%
21	MPGF	Propane (100%)	5079				100.00%	99.90%	-0.10%	0.24	18.77%
22	MPGF	Propane (100%)	5079				100.00%	99.70%	-0.30%	0.27	18.07%
23	MPGF	Propylene (100%)	4952				100.00%	99.90%	-0.10%	1.41	17.92%
24	MPGF	Propylene (100%)	4952				100.00%	99.90%	-0.10%	1.36	17.38%
25	MPGF	Propane/N_2 (50/50)	2448				99.97%	99.30%	-0.67%	0.23	19.48%

The FlareSentry directly monitors flare CE, eliminating inaccuracies associated with the current practice of monitoring indirect parameters (heating value, velocity, waste stream speciation, etc). Autonomous operation means the FlareSentry needs no aiming or manual data reduction. Remote mounting and measurement means there is no contact with corrosive process gases. This makes the FlareSentry easy to maintain with a low long term cost of ownership due to lower operation and maintenance costs over the life of the system, when compared to traditional flare monitoring technologies.

The feasibility of the FlareSentry system was first demonstrated in a bench scale test and was recently tested on full scale flares. The full scale experiment was conducted in November 2014 at Zeeco, Inc.'s flare test facility near Tulsa, Oklahoma. Three full scale fares were tested: a 16 in. steam-assisted flare (Zeeco Model QFS), a 10 in. air-assisted flare (Zeeco® Model AFDS) and a multi-point sonic flare (also referred to as a pressure-assisted flare and used as a ground flare, Zeeco® Model MPGF).

For this experiment, flares were evaluated by the FlareSentry at a distance of 300 ft from the base of the flare stacks. In order to validate this new method, simultaneous extractive sampling was performed to evaluate the DRE and CE of the flares. For the extractive sampling, an inductor with a sampling hood was suspended over the flare using a crane, and a portion of the gases captured by the inductor was extracted and transported via a heated sampling line to a monitoring trailer. Inside the trailer, a contracted stack tester continuously analysed samples for combustion products carbon dioxide and carbon monoxide, unburned hydrocarbon and oxygen. The test methods and procedures used were consistent with standard EPA methods for stack testing.

39 test runs were performed covering a CE range of approximately 60 - 100%. The results from the new method showed a strong agreement with the extractive methods. The performance of this new flare monitoring technology is demonstrated by comparing the CE measured by FlareSentry and CE measured by the extractive method, as shown in Table 1.

As Table 1 indicates, the results from the extractive sampling and the FlareSentry were highly correlated, where r^2 = 0.9856. The average difference in two results is 0.50% and the FlareSentry system showed an excellent repeatability.

The FlareSentry system also provides a metric called smoke index (SI) to indicate the level of smoke in the flame. The real time CE and SI outputs from the FlareSentry can be integrated into the flare control system for closed loop

Table 1 continued. Flare CE validation test results											
Test no.	Flare type	Fuel	Fuel flow rate (lb/hr)	Stoichiometric air	Steam/ HC (lb/lb)	CZNHV (Btu/ft^3)	CE-extractive method	CE-new method	CE difference	Smoke index	Avg. O_2 in extracted sample
26	MPGF	Propane/ N_2 (50/50)	2448				99.99%	99.80%	-0.19%	0.35	18.19%
27	MPGF	Natural gas (100%)	3300				100.00%	99.80%	-0.20%	0.26	17.03%
28	MPGF	Natural gas (100%)	3300				100.00%	99.90%	-0.10%	0.32	15.76%
29	QFS	Propane (100%)	4640		0.52	1035	99.99%	98.70%	-1.29%	0.56	19.91%
30	QFS	Propane (100%)	4640		0.52	1035	99.97%	99.10%	-0.87%	0.70	17.60%
31	QFS	Propane (100%)	1879		1.25	571	97.75%	97.50%	-0.25%	0.46	19.90%
32	QFS	Propane (100%)	1879		1.25	571	67.48%	77.20%	9.72%	0.83	20.24%
34	QFS	Propane (100%)	1537		1.53	489	59.99%	73.60%	13.61%	0.17	19.94%
36	QFS	Propane (100%)	1537		1.53	489	70.57%	76.60%	6.03%	0.15	18.75%
37	QFS	Propane (100%)	1537		1.53	489	83.15%	85.10%	1.95%	0.21	18.38%
38	QFS	Propane (100%)	3328		0.71	850	99.67%	99.10%	-0.57%	0.40	17.38%
39	QFS	Propane (100%)	3328		0.71	850	99.82%	99.40%	-0.42%	0.46	18.86%
Average CE difference between the two methods – all 28 tests: 0.50%											
Number of tests with oxygen <19.5% (indication for good extraction): 18											
Average CE difference between the two methods – 18 tests with oxygen <19.5%: -0.10%											

operation, optimising flare operation from both a cost and CE/DRE perspective. Automatic adjustments to fuel or assist gas, steam and air can be made via the closed loop control system, based on real time conditions of the flare system, lowering costs for supplemental fuel and providing more accurate maintenance of required DRE.

Benefits of the FlareSentry include:

- Elimination of inaccuracies associated with the current practice of monitoring indirect parameters (heating value, velocity, etc.) versus direct monitoring of CE.
- Autonomous operation eliminates 'aiming' or manual data reduction.
- Providing SI assists the operator with achieving incipient smoke conditions day and night.
- Continuous data availability provides real time CE and SI to operators for optimal flare performance.
- Non-contact monitoring minimises operating and maintenance (O&M) cost, which is high for indirect monitoring methods because the sensors for these methods are in direct contact with the flare vent gases.
- A short measurement cycle (milliseconds, averaged over seconds to one minute) enables quick response and minimises cost for supplemental fuel.
- An industrial interface allows for closed loop flare operations based on direct CE and SI values.
- Providing CE values along with SI and pilot status gives the operator a complete picture of flare performance with a high level of confidence.
- Simplified monitoring, reporting and compliance activities.

Conclusion

Regulations related to flare operations continue to tighten, but employing the best available technology, such as FlareSentry, to monitor and control the actual CE of a flare system in real time gives operators the necessary tool to meet the challenge.

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